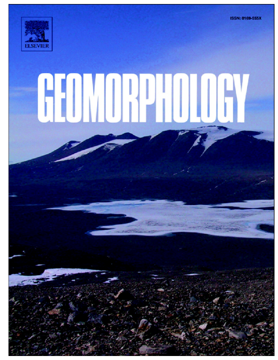
Accepted Manuscript



Rock slope failure in the British Mountains

David Jarman, Stephan Harrison

PII: S0169-555X(19)30088-1
DOI: https://doi.org/10.1016/j.geomorph.2019.03.002
Reference: GEOMOR 6696

To appear in: *Geomorphology*

Received date: 5 July 2018
Revised date: 29 January 2019
Accepted date: 2 March 2019

Please cite this article as: D. Jarman and S. Harrison, Rock slope failure in the British Mountains, Geomorphology, https://doi.org/10.1016/j.geomorph.2019.03.002

Rock Slope Failure in the British Mountains

David Jarman

Mountain Landform Research, Scotland, IV7 8JJ

david.jarman914@virgin.net

***Stephan Harrison**

College of Life and Environmental Sciences, Exeter University, Penryn, Cornwall, TR10 9EZ

* Corresponding author (stephan.harrison@exeter.ac.uk)

ABSTRACT 275 words

In this first full review of extant Quaternary Rock Slope Failure (RSF) in the British mountains, we provide a near-complete inventory of 1082 sites, 40% being rock slope deformations, 40% arrested rockslides, and 20% rock avalanches. Current RSFactivity is negligible, and this relict population is predominantly paraglacial, with a parafluvial minority. Its spatial distribution is perplexing, with RSF density varying greatly, both regionally and locally. In the Scottish Highlands, eight main clusters account for 76% of RSF area in 15% of the montane area. Local concentrations occur in all the British ranges, across high and low relief, in core and peripheral locations, and on varied geological and glaciological domains; as conversely do extensive areas of sparsity, even in similar lithologies. Generic interpretations are thus precluded. Geology is only a secondary control. An association with Concentrated Erosion of Bedrock (CEB) is proposed, as a driver of intensified slope stresses. CEB is most evident at those glacial breaches of main divides where the most vigorous recent incision is inferred, and also in some trough-heads. A clear

association between RSFs and these 'late-developing' breaches is demonstrated in the Highlands, in 42 localities, with sparsity away from them. It is also seen in seven Lake District localities. Glaciological models identify ice sheet volatility capable of driving breach ramification. High-magnitude paleoseismic events are generally unlikely to have provoked RSF clusters; a few candidates are considered. RSF has been underrated as an agent of mountain landscape evolution in Britain; its spatio-temporal incidence may assist in calibrating regional ice sheet models, and in assessing climate change impacts. We argue that the CEB:RSF association has global relevance in identifying primary drivers of mass movement in bedrock.

Key words : rock slope failure; concentrated erosion of bedrock; paraglacial; glacial breach;

1. Introduction – RSF terminology and scope of paper

Rock Slope Failure (RSF) is a major geomorphic process embracing rockslides, rock avalanches and rock slope deformations on a hectometric and often kilometric scale, and penetrating slopes to depths of tens or even hundreds of metres. Although RSF also affects escarpments, plateau rims, and coastal cliffs, the focus here is on 'montane RSF', that which plays a crucial role in the dissection of mountain ranges (e.g. Korup et al., 2007; Hewitt et al., 2008) during the Quaternary. While studies of individual RSFs and localities abound, comprehensive range-wide montane RSF inventories are scarce, both globally and for the British mountains, and this has been identified as a clear research gap (Crosta and Clague, 2006). In addition, these essentially relict paraglacial RSF populations may shed light on how mountain landsystems respond to climate change (Knight and Harrison, 2013). The factors driving the overall spatial and temporal incidence of RSF remain poorly understood. National landslide inventories are generally unsystematic and primarily record recent events with hazard implications, often in soft or superficial deposits (van den Eeckhaut and Hervás, 2012).

1.1. Terminology

RSF studies and inventories are also beset by confused terminology. Firstly, the very term 'failure' is often interpreted *sensu stricto*, typically for engineering geology purposes, as 'the single most significant movement episode ... which usually involves the first formation of a fully-developed rupture surface' (Hungr et al., 2014, p.169). This excludes rock slope deformations (RSDs). However, in practice this distinction defies mapping at inventory scale, with larger sites often comprising both modes.

For mountain geomorphology purposes, 'failure' is better interpreted *sensu lato,* with dictionaries offering not just 'the act of failing' but also 'decline or loss in strength'. The term RSF is thus defined here as :

"any substantial rockmass exposed to slope gravitational processes which has lost structural integrity, regardless of its degree of disintegration or distance travelled" (the qualifier 'substantial' requiring a threshold size appropriate to the context, to exclude trivial cracks and rockfalls, see 2.2 below).

'RSF' thus provides a clear 'umbrella term' spanning all modes of behaviour from fracturing, creep and deformation, via sliding of coherent masses, to complete collapse. As well as mass movement downslope, it includes outward and upward (rebound) displacements. This *sensu lato* usage has become adopted by anglophone geomorphologists (Holmes, 1984; Ballantyne, 1986, 1997, 2013; Wilson et al., 2004; Hutchinson, 2006; McColl, 2012). Early RSF inventories (Holmes, 1984; Fenton, 1991) included many RSDs and sites with 'diffuse margins'. It is also gaining acceptance in Europe (Braathen et al., 2004; Jarman et al., 2014a; Pànek et al., 2018). It is more precise than the traditional terms 'landslide' and 'mass movement' which usually embrace RSDs (Clague and Stead, 2012; Lebourg et al., 2014), but include events in superficial deposits.

This broader umbrella reflects progress from mechanical back-analysis of landslides to computer modelling of slope stresses. The former identifies peak or residual friction angles (Holmes, 1984) and thus discrete failure surfaces on bedding planes and joint sets. The latter recognises that mountainsides are typically close to critical thresholds of stability (Watters, 1972; McColl, 2012): where they become overstressed they can be restored to metastability by:

- rockmass shedding – the slope is pared back to a clean break where stress falls below critical thresholds. The material is shed as a rockfall, rockslide, or rock avalanche; or
- re-equilibration – the excess stress is dissipated within the rockmass by micro-fracturing or thin slicing, and accommodated by bulging or dilation. The area affected is a rock slope deformation, and thus becomes more resilient (akin to sea defences of coarse blocks, or movement joints in structures).

Both represent failure, and are on a continuum, with rockslides able to move on multiple planes or 'zones of crush' (Blikra et al., 2012; Jarman and Wilson, 2015a).

The second problem for RSF inventories is that elaborate standard 'landslide classifications' (Varnes et al., 1978; Hutchinson, 1988, 2006; Hungr et al., 2014) are intended for site-specific engineering analyses rather than regional classification and interpretation. Variant

terms proliferate, such that a Rock Slope Deformation can be a sackung/sagging/creep/spread/slump, a 'rock slope instability' (Böhme et al., 2011), or permutations of large, deep-seated, and gravitational (most cumbersomely DSGSD) - witness Pànek and Klimes, 2015 versus Pànek et al., 2015). Rampant confusion frustrates comparisons between sites and regions (SF2.23). The simplified schema devised by Jarman (2006) for the Scottish Highlands has been used successfully in British and European contexts (e.g. Ortuño et al., 2017; Blondeau, 2018 - albeit in translation). A similar three-way schema (McColl, 2012) combines rockslides and rock avalanches, but introduces a 'rockfalls' category, with its threshold size issue (see 2.2). This problem of consistent terminology remains unresolved, but aided by lengthy discussions (SF2.24), the typology has been refined for this Inventory (Fig. 1).

1.2. Paraglacial RSF

It has become axiomatic that in glaciated mountain ranges, RSF is primarily paraglacial (Ballantyne, 2002). In the glacial–paraglacial cycle (Jarman, 2009), RSF prepares slopes for accelerated glacial erosion, and enhances debris supply to moraines, rock glaciers and ultimate export to sediment sinks. Quantification of extant RSF incidence inherited from the last glacial cycle helps calibrate paraglaciation exhaustion models (Mercier et al., 2017).

Dating of paraglacial RSFs is inherently difficult, with delicate RSD features liable to degradation over millenia, coherent rockslides lacking good exposures, and the most easily-sampled rock avalanche blocks sometimes resulting from secondary collapses. It is assumed that most RSF occurs during or soon after final deglaciation, with a tailing off into the Holocene. Some may predate final deglaciation, if the last glaciers have been insufficient to rework them beyond recognition. In the British mountains, which were repeatedly submerged by the British-Irish Ice Sheet (Clark et al., 2012), the limited evidence supports this pattern (Ballantyne et al., 2014); there are very few cases in recorded history let alone still active. The same appears typical globally, except in ranges of high tectonicity.

Space here precludes a review of the global paraglacial RSF literature, for which see McColl (2012), also Pànek and Klimes (2015) for RSDs, and Grämiger et al. (2017, 2018) for slope stress theory. However, the British inventories here presented appear to be the first for

whole ranges in Europe, excepting Iceland (Whalley et al., 1983), a special case of basalt plateau rim and fjord coast character. Valuable inventories exist for two sectors of Norway (Blikra et al., 2006), the Upper Rhône (Pedrazzini et al., 2016), and the eastern Pyrenees (Jarman et al., 2014a). Other major inventories are for RSF sub-types (Böhme et al., 2011; Crosta et al., 2013) or events in recent recorded history (Eisbacher and Clague, 1984; Wood et al., 2015). As more comprehensive inventories emerge (e.g. Blondeau, 2018 for the western Alps), consistency in terminology and mapping criteria will aid intercomparability.

1.3. Scope of paper

While RSF is largely a paraglacial response to glacial erosion, this is only a driver conditioning the terrain. RSF incidence is often abundant in glaciated ranges, but still only affects small percentages of montane area or valley walls. Understanding the causes and triggers determining its sporadic spatio-temporal distribution is still in its infancy, in a mountain slope-stress context.

The full montane RSF inventories now presented for the first time for the British mountain ranges (sections 2.1-2) enable these underlying drivers, causes, and event triggers to be addressed. The main aim of this paper is to comprehend the marked clustering and sparsity originally identified with large RSFs in the Scottish Highlands by Jarman (2006) and confirmed in the present analysis (sections 2.3-4).

Previous explanations for RSF (section 2.5) having been found inadequate to account for this pronounced clustering, Jarman (2006) identified a strong association with glacial breaches (see section 3), where a hypothesised Concentrated Erosion in Bedrock (CEB) may have intensified rebound stresses (section 4). Regional patterns of RSF around breaches and in other CEB locations are evaluated in Section 5 to assess this CEB:RSF hypothesis. The main conventional explanations for RSF incidence - geology and seismicity - are then reviewed in light of the regional evidence (section 6). Curiously, areas of rapid current valley deglaciation globally are not reported as displaying high RSF incidences; this is discussed in section 7.

2. Development of the RSF Inventory for the British mountains

Systematic RSF mapping in the British mountains began with British Geological Survey (BGS) work in selected field areas in the Scottish Highlands, with some remarkable early perceptions of their significance (Clough, 1897; Bailey and Maufe, 1915; Peacock et al., 1992). This provided a basis for pioneering research (Watters, 1972) and the unpublished inventory of Holmes (1984). His 364 sites were augmented from BGS and other sources to 495 by Ballantyne (1986). In the Lake District, Wilson et al. (2004) listed 48 sites. No inventories have been published for the Southern Uplands or for Wales, although several major RSFs have been reinterpreted (Jarman, 2010a). These problems of consistency and verification are common (van den Eeckhaut and Hervás, 2012).

The BGS landslides database (Foster et al., 2011) currently has 1100 entries in its Domain 5 which approximates the montane area (Dashwood et al., 2017). However it is an acquired compilation not a systematic survey; it includes landslips and debris flows in superficial deposits, often minor; it is not open access; and its natural focus is on recent reported events with hazard implications, often roadside or riverside. Not all BGS sheets map RSFs; they are hatched as 'landslips' but generally only where there is obvious disturbance of bedrock; they exclude cavities. Landslides are not shown on the BGS online map.

2.1. The 1082-site British montane RSF Inventory – sources and verification

The Inventory presented here now encompasses all the older British mountains, defined as Caledonide with pre-Devonian rocks (Fig. 2). It excludes the younger uplands where RSF can be extensive if simpler, often with competent cap rocks overlying less-competent strata - southern Wales, the Pennines, Cheviot, and the Paleogene volcanic province of Scotland (e.g. Trotternish, Ballantyne 2007a). The October 2018 dataset of 1082 RSFs is seen as near-complete, although augmentation continues, by 79 since April 2015 (Table 1). It is being incorporated into the BGS database.

Data sources include air photos (1988 Scotland series, superior to the 1948 series available to Holmes); satellite imagery (systematic Google Earth search including Historical Imagery, augmented by Bing Maps); 1:25,000 topographic map interpretation; and extensive field exploration. DEM imagery (e.g. NextMap) is less helpful than satellite imagery, which is in

colour, shows vegetation and drainage contrasts, and affords natural light views from any angle. Its quality is variable, and even with good contrast, subtle RSFs may go undetected. Montane RSF identification is only occasionally hindered by afforestation: LIDAR can penetrate this but is not generally available. The Inventory for Wales relies most on satellite imagery, and may be less complete. The Highlands and Lake District totals of 920 and 77 sites mark 46% and 33% increases on previous published inventories.

Nearly all the sites have been visited or clearly seen in the field or on imagery (Table 1). However, relict RSFs can be difficult to distinguish from other mimicking landforms and deposits (Jarman, 2010a; Jarman et al., 2013), and a criteria-based approach is taken in the inventory, applying the indicators of Holmes (1984). Thus 71% are rated ‘definite’ RSF and 15% ‘probable’, with 14% still only ‘possible’ despite half of these having been field-visited (Fig. 3; SF2.17-20). This approach to RSF identification recognises uncertainty as inherent in geomorphological mapping, and is a valuable corrective to yes-no labelling; it could be extended to embrace cavities and modified RSFs from earlier glacial cycles.

2.2. RSF size, character, age, and extent

For the term ‘RSF’ to be of utility, a threshold size must be defined. This inventory follows the 0.01 km^2 (~100x100m) criterion adopted by Holmes (1984), thus excluding “abundant minor slips and rockfalls and other downslope movement” (British Geological Survey, 1987). The ~150 ‘RSF’ dataset of Cave and Ballantyne (2016) in the NW Highlands has no qualifying size; it is unavailable for verification, but such minor features probably predominate. Nevertheless, small sites can have considerable impact on local landscapes. An ‘operator bias’ against identifying very small sites (or towards amalgamating them) became evident, and redressing it has significantly expanded the Inventory. The usual log-normal size distribution (Fig. 4) has 28% very small (0.01-0.05 km^2) and a tail of large RSFs (>0.25 km^2), and very large RSFs (Beinn Fhada, 3.00 km^2 - SF4). A size plot of the BGS landslides database (Hurst et al., 2013) identified an abrupt tailing-off at the large end, which may reflect under-recognition of older and more remote montane sites including large slope deformations.

Following Holmes (1984), RSF extent includes both cavity and deposit (Fig. 1). With RSDs, diffuse margins can make defining failure extent problematic. Some larger sites have ‘definite’ cores and extensive ‘umbras’ rated only ‘possible’.

RSF size is remarkably consistent across montane Britain. Average RSF size is 0.18 km^2, and only markedly less in the Southern Uplands (Table 1). Of the 23 Highland Inventory Areas (Table 2; SF1; SF2.2), only four exceed this size norm by more than a third: they occur where relief is greatest or conditions favour extensive slope deformation. Conversely the six Highland massifs of significantly smaller average RSF size are all peripheral with lower relief. Large sites >0.25 km^2 are widely distributed, on high and modest relief alike (see Fig. 5). Such consistency suggests a prevailing landscape control on available widths and heights of valley-wall segments.

RSF character is defined in the simplified schema (Fig. 1) by key criteria of travel distance and degree of disintegration:

main type	mode	travel distance	disintegration
(1) rock slope deformations	(a) extensional	limited	opening, bulging
(RSDs)	(b) compressional	quasi-in situ	fracturing
(2) rockslides	translational	arrested	coherent fabric
(3) rock avalanches	(a) cataclasmic	slope foot	complete
	(b) sub-cataclasmic	lower slope	substantial

Thus the classic ‘arrested translational rockslide’ (type 2) has a clear cavity and a failed mass, much broken up but moved as a body without collapsing. Deformations may have headscarps if extensional, but lack cavities or clear flanks.

Rock avalanches comprise 20% of the British population (less by area), but are mainly sub-cataclasmic (Fig. 1d), with only 4% fully cataclasmic (a more objective term than ‘catastrophic’). None are ‘sturzstroms’with excess run-out lengths, with the most spectacular being on (3.5 Mm^3 and dated to around 4300 BP by Ballantyne, 2007b). Thus few rockslide dams exist: Tal-y-Llyn in mid-Wales (Hutchinson and Millar, 2001) is exceptional.

Arrested rockslides and RSDs account for about 40% each in most mountain regions, with perceptible bias to rockslides only found in the Northern Highlands, and to RSDs only in the Southern Uplands (on Ordovician shales) and Lake District (on Borrowdale metavolcanics).

RSF occurs in diverse locations, including valley walls, plateau rims, ridge crests, truncated spurs and escarpments, shaping the mountain landscape. Only 15% of Highland RSFs (half that by area) are associated with cirques, and 11% in the Lake District, contributing to their enlargement but also destruction. In cirques and trough-heads, RSF is commonly on their flanks, since headwalls possess self-supporting concave architecture and erode more incrementally. The anomalously high 44% found in cirques by Cave and Ballantyne (2016) may confirm they are mostly sub-RSF rockfalls.

Just under 5% of Highland RSFs are in fluvial valley contexts, of both pre- and post-glacial origins (SF2.16). Where these are not directly provoked by stream incision, they can be described (by analogy with paraglacial RSF) as 'parafluvial' (as defined in Jarman et al., 2014a). Indeed fluvial/parafluvial RSF becomes dominant in the Southern Uplands, Lake District fringes, and mid-Wales (Figs. 6-8 below), with adjacent glaciated and non-glaciated valleys displaying similar RSF clusters, perhaps calling into question the 'paraglacial driver'. Since fluvial erosion is also generally incremental, normal fluvial mountain valleys rarely display significant RSF. Gorge slots do not involve bulk erosion of bedrock. Cases tend to be sui generis, but often suggest rapid incision in meltwater channels. Abrupt undercutting of rock masses may be the simple mechanism in such cases, notably the string of 10 RSFs along the Water of Ailnack channel (eastern Cairngorms).

RSF ages are mostly unknown, and dating is difficult: many RSFs have evolved into multiple components (Fig. 1c), with the freshest debris possibly reactivated, and original scarps too subdued to sample. A special problem arises with the final Younger Dryas (YD) glacial episode (~12900–11700 BP), which briefly covered much of the western Highlands, and reoccupied Lake District and Snowdonia trough-heads. Most RSFs would probably yield early Holocene dates, but are they responding to this final episode, or are they a delayed response to the main Late Devensian (before 15000 BP)? Within YD limits, Lateglacial RSFs

(Ballantyne, 2013) may lack deposits, with cavities merely 'debris-free scarps' (Holmes, 1984); or have deposits glacially reworked to mimic moraines (Jarman et al., 2013; Ballantyne, 2018). Beyond YD limits, earlier RSFs may be subdued by periglaciation. The Inventory is thus not a single age-group of Holocene RSFs; it will include well-evidenced events which may be syn- or even pre-Lateglacial (e.g. Jarman and Wilson, 2015a, 2015b), but excludes more speculative cases (e.g. Carter, 2015; Ballantyne, 2018). All these caveats must qualify the only British dating study (Ballantyne et al., 2014), which is necessarily restricted to sampling the minority group of fully-disintegrated failures; of its 17 sites, only seven are on the prevailing schists, which rarely yield cataclasmic RSFs.

The total extent of RSF in the British mountains, 191 km^2, is only 0.6% of the montane area (Table 2; SF1). Although this includes plateaus, valley floors, and gentle slopes below the typical ~20° threshold for failure, this is still an apparently trivial figure (nevertheless, the New Zealand Southern Alps attain only 2% - Allen et al., 2013). In most Highland massifs RSF affects <10% of valley walls (Jarman, 2009). Despite RSF being so infrequent, it is widely distributed across all the older mountain areas. Even where most prevalent, it affects only a minority of available slopes. This enigma provides the focus and challenge for this paper: to identify and interpret core areas where RSF incidence becomes significant, especially the densest clusters within them.

2.3. RSF clustering and sparsity - Scottish Highlands

An initial overview of large RSFs (>0.25 km^2) in the Highlands (Jarman, 2006) found that the majority fell within seven main Clusters. This holds good, both with the full ~850 population, and with the large sites array updated from 140 to 175 (Fig. 5). Conversely, extensive tracts within the montane area still remain almost devoid of RSF, despite apparently similar relief and geology (SF2.3).

The full Inventory allows these seven clusters to be reappraised. Two fall well below a 'significant density' of 4% of cluster area (or 5x range total of 0.8% of montane area). Cluster 6 could be reclassified as two 'local concentrations', while Cluster 4 is revealed as a grouping of large RSFs unsupported by a matrix of lesser cases. A Cluster 8 now identified in Glen

Almond had been overlooked by Holmes (1984) in peripheral low relief, and only emerged when satellite imagery improved, confirmed by intensive groundtruthing and new BGS work (Maarten Krabbendam, pers. comm. 2016).

These eight Highland Clusters account for 65% of the total RSF population and 76% of its areal extent, despite comprising only 15% of the montane area (Table 3). An even sharper demonstration that RSF incidence is far from endemic is obtained by defining core zones within each of the 23 Highland massifs, within which almost all RSFs occur (Table 2; SF1). Excluding only 35 isolated sites separated by more than 5 km (column 8), the remaining 96% of RSFs (97% by area) fall within 25% of the montane area. Even so, overall density only increases to around 3% of massif cores.

The pronounced tendency to RSF clustering is further demonstrated by a total 7% density across 29 local concentrations (mainly 25-100 km^2 in extent) within 10 of the 23 Highland massifs (Table 2; SF1). Of these, 14 local concentrations are outside the eight clusters, in both breach and trough-head locations (Fig. 5; Table 2; SF1). Even zones of sparse RSF usually possess local concentrations >4% density. Certain glens or massifs achieve densities >12%, notably at Glen Ample, Glen Almond, and Loch Ericht; Glen Roy has an exceptional 19.4% (Jarman 2008). These cases are in remarkably limited relief, with troughs incising only ~500 m into intermediate altitude (~800m asl) plateaux. Such high densities are usually attained where long trough walls favour large-scale slope deformation, and are harder to achieve in more dissected and mountainous terrain, although the high Mamores and Cluanie–Affric massifs exceed 7%. Individual valleysides can demonstrate startling intensities - in modest Glen Luss (Cluster 5), RSF affects half of the north-side valley wall length, inviting the question why not the other half? Detailed assessments of Clusters 1/3/5/6/7 are available in Field Guides (Jarman, 2003a, 2003b, 2004, 2008); as conversely of areas of sparsity with local RSF concentrations (Jarman, 2010b, 2013); and see SF3.

2.4. RSF clustering and sparsity - other British ranges

A broadly similar picture of highly variable RSF spatial incidence prevails across the other British mountains. Only the English Lake District attains a similar overall RSF density to the

Highlands, with 71 RSFs in its compact extent (Fig. 6). Half are within two 'cores' with densities of ~3%. More notably, the majority of this massif displays little or no RSF, including most of the main glaciated trough sides, the central areas, and south of the main divide.

The Southern Uplands (Fig. 7) and Wales (Fig. 8) have much lower RSF incidence, a quarter of Highland density, reflecting their less dissected character. Remarkably, 62% of Southern Uplands RSFs are concentrated within 2% of the montane extent, in two enclaves where dissection (glacial and fluvial) is unusually intense. In Wales, RSF is surprisingly uncommon and sporadic in the glaciated high mountains of Snowdonia; elsewhere small local concentrations occur within a thin scatter, mainly in a few mid-Wales trough-heads.

RSF incidence is thus highly concentrated both regionally and locally across all the British ranges. Although numbers and peak densities are very substantial for a non-alpine mountain province, they have gone largely unrecognised by geoscientists and especially the Quaternary geomorphology community in Britain. Their landscape evolution impacts (Jarman, 2003a, 2009) range from cirque seeding and glacial trough widening to spur truncation, ridge reduction, destruction of summits, and elimination of paleic relief - the extensive preglacial summit surface (Godard, 1965). Their implications for glaciation history await exploration.

2.5. Explaining RSF clustering and sparsity

Conventional causal models for paraglacial RSF were found unable to account for these remarkably skewed spatial distributions by Jarman (2006). To summarise and update that position we must recognise that:

- endemic factors cannot explain clustering - destabilising events such as trough erosion (valleyside oversteepening) and deglaciation (debuttressing, meltwater abundance) are endemic. They apply to entire mountain ranges, and should provoke endemic RSF along every valleyside.
- predisposing factors cannot explain sparsity - clearly some mountain slopes are more susceptible to failure than others, but while RSF often associates with conducive

geology, structure, or slope aspect, such variables are widespread. They may explain why a specific site has failed, but not why RSF is sparse in comparable contexts.

- triggers are not causes - an RSF may be provoked by a rainstorm, sudden thaw, or earthquake, but these are only triggers on the day, often in a context of progressive weakening over centuries. Triggers are more relevant in risk and hazard studies.
- fallacies of reverse induction - these arise where RSF spatial distributions are invoked to support preconceptions for which temporal information is lacking (see discussion in Harrison 1999). Thus to associate RSF with elevated deglaciation meltwater pressures would require most extant RSFs in the region to be datable to a timespan of a few hundred years; to associate RSF directly with high-magnitude seismic events would require many RSFs in a given radius to date to the same day.

Applying these tests to the principal causes advocated for British contexts, in order of publication, finds:

a) meltwater - elevated joint pressures along Loch Lomond Stadial (YD) ice limits during deglaciation (Holmes, 1984) - endemic and a fallacy
b) geology - conducive lithology and dip (Ballantyne, 1986, 1997) - predisposing factor
c) seismicity - high-magnitude events around deglaciation provoked by regional glacio-isostatic rebound (Fenton, 1991) - trigger not cause, potential fallacy
d) debuttressing - withdrawal of ice support from oversteepened valleysides (Ballantyne, 2002, 2013) - endemic

Meltwater pressure is now generally discarded, because firstly ice limits then thought to be along valleysides are now being widely remapped above valley rims (e.g. Boston et al., 2015), and secondly, glacier recession was highly mobile in time and space, with meltwater abundant throughout valley systems, not merely at maximal ice limits. Nevertheless, water pressure in joint systems is highly influential in activating failure, and has to be factored into a slope stress model. Its role may be enhanced in CEB locations where rebound fracturing is pervasive.

Debuttressing after oversteepening is an apparently attractive explanation for RSF (Beget, 1985), but as an endemic factor cannot account for sparsity along many glacial troughs in fallible geology, whether immediate or delayed. In any case, ductile ice is more likely to deform under the load of a failing rockwall than to support it (McColl and Davies, 2013). Modelling shows glacial debuttressing alone to be ineffective (Grämiger et al., 2017).

Slope aspect cannot be a prime cause, but Holmes (1984) tabulated a marked prevalence on W/SW/S/SE aspects, as widely observed in expanding the Inventory, e.g. Glens Loy and Mallie, Glen Luss (Figs. 12 and 15 below). Paucity in the NE quadrant reflects the aspect of cirques, where concave architecture, incremental erosion, and short slope facets resist failure above the scale of rockfalls. Conversely, the favoured aspects have extensive open slopes conducive to larger-scale RSF, and possibly higher periglacial and thermal stresses on aspects with high insolation (Brardinoni et al., 2003).

Leaving the secondary roles of geology and seismicity for review in Discussion, the search for a prime cause has long recognised that (to paraphrase Holmes, 1984) “some factor is needed to augment the usual stresses acting on a mountain slope” to provoke failure in selected localities while most remain intact. The most promising factor to emerge in Jarman (2006) was differential rebound in valley segments subjected to unusually intense recent glacial erosion, notably in breaches. This would account for RSF clustering around what may be termed ‘late-developing’ glacial breaches and trough-heads. However, the only supporting data then available to test this was that 75% of the large-RSF population lay within ~2 km of a putative glacial breach of a main or secondary divide. This association can now be addressed with the benefit of a comprehensive RSF inventory - once the concepts of glacial breaching, ice divides and slope stress modelling have been clarified.

3. Glacial breaching of divides

It is of interest for historians of geomorphology that the term ‘glacial breach’, once a staple of physical geography (e.g. Sparks, 1960), has fallen into disuse, perhaps as unamenable to dating or quantification. Long recognised in the Alps and Norway, it was discerned in the Highlands by Linton (1949), Dury (1953), and Godard (1965). It was still well defined in a

specialist dictionary (Allaby and Allaby, 1990), but rates no main entry in the Encyclopaedia of Geomorphology (Goudie, 2004). In the first edition of Benn and Evans (1998) it had a cursory mention with atypical illustration; in the second it has none. In Evans (2103) it has one. Google Scholar offers negligible mentions post-2000. It appears unknown to students, and thus merits restating.

3.1. The breaching process

Breaching occurs where glacier ice overtops its confining terrain, whether a valley rim or mountain crest. It can be a simple *diffluence* where a glacier forks across a col, with the outlets descending into the same main catchment. With glacial *transfluence*, ice crosses a range divide into an entirely separate catchment. To do so, the glacier may utilise a pre-existing col, performing only minor adaptations to its shape and capacity; or it may greatly enlarge it and the route downstream, cutting a 'transectional breach'. Thus the extent to which an apparent breach of a main divide is wholly, partly, or minimally glacial in origin can vary greatly, even in the same range.

Where glaciers overtop the valley systems and coalesce as an ice cap or ice sheet, an ice divide or *ice divide* will become established. This may initially be coincident with the topographic divide below, but can become offset from it where landmass or precipitation are asymmetric. The ice divide will migrate as the ice sheet waxes and wanes, or if climatic inputs alter, or where discharge routes shift, or even as the underlying topography erodes (e.g. Sugden et al., 2014).

As soon as an ice divide becomes displaced from the topographic divide, even by a kilometre, it becomes a potentially powerful driver of breaching through any available dip (SF2.5). The erosive capacity will depend on ice flow through the col being thick and rapid enough to be warm-based; on the efficiency of discharge (draw-down effect); and on ice replenishment rates in the augmenting catchment. Maximum impact is achieved where glaciers descend directly to an ocean, with a thick ice sheet centred behind a topographic barrier, and with discharge impeded on the inland side - as in western Britain, Norway (Bonow et al., 2003), New Zealand (Rowan et al., 2013), NW America (Riedel et al., 2007),

and Patagonia. This gives rise to a positive feedback loop, with breach incision increasing catchment volume and discharge rate, often contributing to 'ice stream' development. Drawdown of ice through such breaches has memorably been termed 'ice piracy' (Bradwell et al., 2008).

Breaches of glacial transfluence can thus be 'windows' - cols where the hydrographic divide is unaffected - or 'doorways' (Fig. 9; Rudberg, 1993). In some through-ways, the postglacial drainage is reversed, capturing stream catchments from the inland side, and so displacing the *'present watershed'* (in the British usage). Characteristic 'agnor' or fish-hook river courses (Bonow et al., 2003) are well seen in Lochaber (Fig. 12 below) and Norway.

3.2. Modelling British ice divide migration

All the British mountain ranges have supported initially independent ice caps, broadly centred over topographic axes. At glacial maxima, their convergence as the British-Irish ice sheet (BIIS) has tended to displace constituent ice divides east (inland) from west-centred topographic divides (Linton 1949). Ice outflow has been relatively inhibited to the east, with longer, lower-gradient distances to the shallow (often dry) North Sea basin, further congested at maxima by the Scandinavian ice sheet. Ice flow to the west has been relatively unrestricted, whether directly into the Atlantic with calving in deep water, or by the vigorous Irish Sea ice stream (Clark et al., 2012). This clash of topography with ice dynamics has promoted conditions favourable to glacial breaching in most British mountain areas.

Climate has influenced breaching potential, with a maritime glacial environment favouring ice accumulation and warm-based outflow on the western ranges closest to the Atlantic. Here, breaching extends below current sea-level, creating islands such as Skye, Mull and Bute. By contrast, drier conditions have prevailed inland, with reduced snowfall and thinner, more cold-based ice (Glasser, 1995). Thus in Scotland, intense breaching and dissection in the west (Haynes 1977) reduces eastwards and northwards (Linton, 1959, and in Clayton, 1974; Fig. 9; SF2.3). Indeed, some of the densest breaching activity may be responding to quite modest ice divide offsets, cyclically reinforced over repeated ice sheet build-up and

decline phases, rather than requiring wide offsets at the few great maxima (e.g. Orchy-Lyon, Fig. 18 below).

Two recent modelling exercises enable spatial patterns of ice divide fluctuation and thus breach evolution to be visualised:

- Hubbard et al. (2009) model the growth, behaviour, and decay of the last BIIS. Rapid pulsing of advance and retreat cycles graphically convey the volatility of the ice divides (SF2.6). Although the model is not intended to be locally accurate, it is possible to drill down through its hundred-year timepoints at any given location to sense if and when breaching might have been favoured.
- Hughes et al. (2014) used palaeoglaciological inversion to provide a ten-Stage reconstruction of the last British Ice Sheet, interpreting the glacial landform record. Ice divide migration patterns can be detected at sufficiently fine resolution to tentatively attribute particular breach groups to certain Stages (Fig. 10). Oscillating transfluence directions could power ‘see-saw’ incision, possibly making breaching very rapid.

Breach freshness and RSF incidence may become useful controls in testing such models as their refinement increases.

3.3. Paleodivides and breach locations

To pursue a CEB:RSF association, with glacial breaches as prime candidate, it is necessary to know where the breaches actually are, and thus where the topographic divides were when glaciation began - the ‘paleodivides’ (Fig. 11). This is because the present watershed has often been displaced by drainage reversal through breaches. This may be evident where it now wanders incongruously across lower ground such as Rannoch Moor (Fig. 5), but less so amidst high mountains such as Glen Shiel.

In the other British ranges, minor local divide displacements are readily inferred (Figs. 6-8), but in the Highlands, this has proved problematic, on two timescales:

- Quaternary: the 'preglacial divide' proposed in Jarman (2006) (Fig. 5) was reasonably reconstructable within massifs, from summit surface remnants (Godard, 1965), headwater and upper slope orientations, and reversals or abrupt changes of drainage direction (e.g. Fig. 12a). However, linking between massifs, and the far north, prove much more difficult (hence options in Figs. 5, 11).
- pre-Quaternary: this divide migration has a long, complicated, and largely unknown descent from original 'protodivides' emplaced during the Caledonian Orogeny, some elements of which persist (Macdonald et al., 2007). The indicative reconstruction of 'paleodivides' (Fig. 11) has them evolving in response to major tectonic events (perhaps during end-Caledonian, end-Variscan, Paleogene). It suggests the first-order controls within which the preglacial landscape evolved its final form. Some apparently glacial breaches may thus simply have colonised Cenozoic or even earlier fluvial incisions into or transecting the range axis. This particularly complicates interpretations in the NW and SW Highlands, also in mid-Wales.

As it is usually impractical to distinguish the immediately preglacial divide from an earlier paleodivide location, the latter term is preferred. Since there are no modern overviews of British divide evolution, and the paleodivides suggested by Sissons (1967) and Hall (1991) for Scotland are schematic, a fuller account is offered in SF5.

3.4. Patterns of glacial breaching in the British ranges

This landscape inheritance has interacted with climate volatility to yield wide variations in breaching style and intensity:

1. perforated main divides – window and doorway breaches so closely spaced that interfluves are serrated, with little if any paleic relief surviving, e.g. West Highlands (Fig. 12b); Lake District (Fig. 6b);
2. plateau transection – isolated breaches sharply cutting extensive paleic relief, e.g. Central Grampians - Cluster 6, Fig. 12a);

3. cross-grain breaching – across secondary divides running athwart ice sheet gradients; can be ‘ridge-hopping’ sequences across several parallel divides, e.g. west Perthshire; west of Great Glen;
4. lattice patterns – either synchronous, where ice flow over a peripheral massif has developed anastomosing channels through a ‘braided’ breach network; or diachronous, where shifting ice divides have driven cross-cutting breach arrays, most notably west of Loch Lomond (Fig. 14 below).

Some breaches are short and obvious, others more extended. Where a through valley has a paleodivide at one end and present watershed towards the other, as at Glen Shiel, the breach is effectively 5-10 km long (SF3-8), albeit erosion has been most concentrated around the paleodivide. Breach dimensions vary greatly (Fig. 9).

3.5. Breach age

Breaching will have commenced as soon as ice sheets began overtopping divides, with greatest incision rates probably during the mid-Pleistocene maxima. Latterly, during the Devensian, most breaches may merely have been reoccupied. Only where climatic variation generated new ice divide locations and dispersal patterns would breaches be much enlarged, or newly cut. The ‘freshness’ of apparent breaches indeed varies markedly. However no dating studies in Britain have yet distinguished more recent from older breaches, or indeed from preglacial valleys only lightly modified by ice.

In considering the association between divides, breach erosion, and RSFs, these wide variations in breach age and character must be borne in mind. Before assessing specific breach groups in relation to RSF clusters (Section 5), the CEB:RSF interaction must be examined in the context of slope stresses.

4. Rebound from CEB as a driver of RSF

The proposition that differential rebound lies behind RSF clustering in the glaciated British mountains follows a lengthy chain of reasoning:

1. "some factor is needed to augment the usual stresses acting on a mountain slope" to provoke slopes to fail at all (Holmes, 1984).
2. this augmenting factor must be geographically localised - if it were endemic, RSF would pepper all deglaciated trough walls, whereas most trough walls are devoid of RSF.
3. RSF probably was endemic during earlier glacial cycles, when fluvial valley profiles were undergoing drastic remodelling and enlargement to accommodate ice discharge (Evans, 1997); present RSF incidence is no guide to past.
4. in a glacial–paraglacial positive feedback loop, ice steepened the slopes and RSF relaxed them, while preparing them for further trough widening in the next cycle (Jarman, 2009; Agliardi et al., 2013).
5. as troughs became well adapted to efficient ice discharge, this cycling weakened and RSF incidence faded, because (i) glacial erosion rates dwindled, and (ii) repeated glacial–paraglacial cycles exhausted the supply of slope segments most susceptible to failure: by analogy with metallurgy, maturing troughs become 'stress-hardened' (SF2.8).
6. extant RSF incidence associates markedly with selected glacial breaches and trough-heads, implying they have undergone unusually intense glacial incision or excavation in recent cycles.
7. such 'immature' late-developing breaches and trough-heads are prime locations for Concentrated Erosion of Bedrock (CEB) in their floors and lower slopes.
8. recent CEB augments other factors to provoke RSF by inducing intra-valley rebound stress differentials between lower and upper slopes.
9. given that even in CEB locations, RSF only affects limited extents of valley sides, the augmenting rebound factor requires favourable conjunctions of other factors to exceed stress thresholds and provoke failure.

4.1. Rebound stress

Rebound is the end-member and most recondite RSFmode in Hutchinson (1988); but has only a passing mention in Hungr et al. (2014). It is exemplified by 'quarry-bursting' where the floor can rupture explosively in response to local removal of tens of metres of rock. Likewise, in a glaciated trough where erosion has been vastly greater in the valley floor than

at the rim, the stress differential can re-equilibrate by rupturing the floor or lower slope. Such intra-valley effects differ from the range-wide neotectonic faulting of Persaud and Pfiffner (2004). Isolated lineaments are occasionally mappable as proto-RSDs (SF2.15) but usually propagate into extensive deformation, rocksliding and collapse (Ustaszewski and Pfiffner, 2008); RSFs often have controlling antiscarps of rebound rupture origins (Jarman, 2003c).

Glacio-isostatic rebound from ice sheet unloading is well documented, including regional variations possibly influencing RSF incidence (Cossart et al., 2013; Peras et al., 2016), but valley-scale effects of differential floor–rim ice thickness are not. However, they are endemic as with debuttressing, and cannot explain RSF clustering.

Differential rebound from bedrock-floor erosion clearly augments this endemic intra-valley glacio-isostatic unloading (SF2.9-10), but no equivalent term exists. It has hardly been recognised (cf. Matheson and Thomson, 1973); whether it can geophysically provoke RSF remains unclear. However Grämiger et al. (2017) demonstrate that ‘rock debuttressing’ by even minor bedrock erosion promotes rockmass damage and consequent RSF.

Invaluable geodetic evidence for rebound-related RSF is provided by the Parallel Roads of Glen Roy (Sisssons, 2017), where metre-scale dislocations (Sissons and Cornish, 1982) associate closely with dense RSF incidence in a glacial breach, and are exclusively upwards (Jarman, 2008; SF2.11-14).

4.2. CEB incision rates in late-developing breaches and trough-heads

To achieve rebound stresses high enough to provoke RSF clusters, CEB would have to be intense in both space and time. Measured glacial erosion rates in hard bedrock are typically only 1-3 mm/yr (e.g. Egholm et al., 2012), requiring most of the Pleistocene to cut a typical 300-500 m-deep breach or trough-head. These studies are however in ‘mature’ troughs. To achieve the CEB needed to cut ‘late-developing’ breaches within the last glacial cycle(s) would require much faster rates (possibly by an order of magnitude). If so, this implies that

glacial incision can occasionally operate on a 'catastrophic' scale, analogous with meltwater flood channels (Matheson and Thomson, 1973).

With glacial breaches, rapid incision can be envisaged where 'ice piracy' augments and accelerates ice discharge. In short valleys descending to the west coast, steep glacier profiles through breaches will increase basal sliding and erosion (Shuster et al., 2011). RSFs on breach/trough walls release debris to the valley floor as 'sandpaper' for use by subsequent glaciers (Jarman, 2009). Pre-existing cols often occupy geological weaknesses readily exploitable by ice. Volatile ice sheet behaviour generates surges, frequent erosive advances, and see-saw incision; new outflow directions favour cross-cutting breach inception.

With trough-heads, rapid incision is less easy to envisage. They occur mainly in eastern/northern precipitation shadow areas of limited glacial dissection (Sugden, 1968). Where they support RSF mini-clusters, it implies they are latecomers to glacial conversion. They often grade steeply or hang into main valleys, favouring rapid erosion (Sternai et al., 2013). Repeated cirque glacier advances down troughs may exacerbate stress damage to valley walls (Jarman et al., 2014a; Grämiger et al., 2018). Where plateau ice descends into trough-heads, a transition from cold-to-warm-based ice (Boston et al., 2015) may drive CEB. Since trough-heads act as sumps draining the plateau, recent ice cover intensification or ice divide shifts would drive their rapid enlargement (Jarman, 2013).

This potential CEB:RSF interpretation is complicated by the Younger Dryas (YD) episode (2.2 above). The Last Glacial Maximum (LGM) peaking ~20 ka BP is when bulk erosion in breaches and trough-heads would have last occurred. The YD performed negligible bedrock erosion in 1200 years (Sharp et al., 1989; Harrison et al., 2010), even in breaches. Extant RSF incidence is thus primarily a response to the LGM, either delayed into the Holocene, or modified by YD glaciers which reoccupied most breaches and trough-heads - thus subduing many manifestations of initial rebound rupturing (Ballantyne and Jarman, 2007).

5. Evaluating the CEB:RSF model in the British mountains

Ideally, these rebound and CEB explanations for RSF incidence would be mathematically modelled and quantified. This is problematic here on three levels. All are challenges to be addressed, but they may account for the neglect of this subject in geomorphology.

Firstly, multivariate analysis of RSF incidence (cf. Crosta et al., 2013) runs up against the philosophical difficulties outlined in 2.5 above. It will tend to identify predisposing factors, causes and triggers where RSF has occurred, without explaining why they have been ineffective where it has not. It does not reach the underlying drivers. And since timing of failure is seldom known, it will tend to perpetuate fallacies of reverse induction.

Secondly, the 'objects of study' are imprecise. Neither RSFs nor glacial breaches have standard definitions or easily measured volumes. RSF extents are often diffuse, with depths incapable of close approximation. Glacial breaches often have unknown bedrock floors, pre-incision col profiles, and linear extents: neither 2-D cross-sections nor 3-D volumes can realistically be measured. Calculating the rapidity with which CEB occurred requires not just extant breach ages (e.g. Ballantyne et al., 2014) but exhumation rates. Dating statistically-valid samples of the whole RSF population is difficult (2.2 above).

Thirdly, to test the rebound effects of CEB, an integrated 3-D model of all slope stresses acting on glaciated mountain slopes is required (Jarman 2006; SF2.10). Despite recognition of its desirability in many discussions (e.g. Jarman et al., 2014b) it remains elusive. Although sophisticated slope stress analysis now allows understanding of individual RSFs (Stead et al., 2006; Grämiger et al., 2017, 2018), it has yet to be attempted at whole-valley scale. Until such an integrated model is available, into which geodetic data such as Glen Roy can be factored, the CEB:RSF hypothesis is conceptual.

Qualitative approaches have an honourable place in geomorphology (cf. Linton, 1949), and this is the course now pursued, via close appraisal of the RSF inventory in the British mountain landscape. The strength of the CEB:RSF association is simply assessed by:

a) RSF density analysis to identify clusters and local concentrations (Table 2; SF1)
b) enumerating RSFs in breach locations, with strength ratings (Table 4; SF2)

c) associating areas of clustering and sparsity with CEB modes (Table 5; SF1)
d) detailed evaluations of the Scottish Highlands by sector (SF7, illustrated in SF3-4)

The relative contributions of CEB and other factors such as geology and seismicity can then be reappraised.

5.1. The RSF–breaching association

A comprehensive review of RSF incidence in Scottish Highlands confirms a strong geographical association between RSF clustering and CEB in glacial breaches. It identifies 385 (49%) definite/probable Highland RSFs as associated with actual or inferred breaches), of which 330 (42%) are medium to strong associations (Table 4; SF1). This excludes ridge crests, higher-level tributaries, and distal troughs (more than ~5 km down-ice) where some RSFs are likely to have been influenced by breaching. It includes the whole of Cluster 5 (130 sites) as a breach lattice which cannot be disentangled. About 100 breaches (of several hundred) have associated RSFs, including ~20 in Cluster 5. The proportion of all glacial valley walls located in breaches resists calculation, but is unlikely to exceed 20%.

The eight main clusters and most of the local concentrations (Fig. 5) together straddle the main and secondary divides or paleodivides from end to end, and associate with all four styles of breaching (3.4 above), for example:

- perforated main paleodivide - Glen Shiel and Gleann Lichd in Cluster 1 (Fig. 13a), where several of the largest and boldest RSDs occur not at the present watersheds but ~5 km west at the reconstructed paleodivide, where breach incision could attain 800 m (Sgurr na Ciste Duibhe - in Jarman, 2007; Beinn Fhada - Ballantyne and Jarman, 2007).
- plateau transection - Loch Ericht and Gaick Pass in Cluster 6 (Fig. 12a), across the Grampian paleodivide; assuming the ice divide was generally centred over it, these breaches could only have been cut during brief displacements, as Stage 5 in Hughes et al., 2014 (Fig. 10). They are flanked by 7 and 10 RSFs respectively, some large, in a context of extreme sparsity on steep valleysides and plateau rims around.

- cross-grain breaching - in LC4 (Balquhidder), N-S breach sequences cross the secondary Tay/Earn/Forth (paleo)divides, driven by prevailing ice outflow, and flanked by 14 RSFs on highest and lowest hills alike (Fig. 14; Table 4: SF1).
- lattice patterns - Cluster 5 is by far the largest, with some high local RSF densities, and the most intensely breach-dissected (Fig. 14), suggesting that this peripheral and relatively low massif (only one peak attaining 1000m) has stood athwart the most vigorous and recently volatile ice dispersal routes, alternately to the Atlantic and the Irish Sea.

In the Lake District, 13 window and doorway breaches of the range divide and offshoots have 15 closely associated RSFs (Table 4; SF1; Fig. 6). Although only 22% of definite/probable cases, they exemplify the association (e.g. Robinson RSF, Wilson and Jarman, 2015), with sparsity down the main valleys. In Wales, the only RSF group which could associate with CEB along major ice dispersal routes is Cluster 2 around Cadair Idris (Fig. 8). Here the Graig Goch landslide dams Lake Tal-y-llyn in a fault-guided trough (Hutchinson and Millar, 2001); at its head the Cross Foxes window breach is flanked by an RSD.

5.2. RSF in trough-heads

The other principal CEB locus identified is in late-developing trough-heads. In the Highlands, the six such groups (Table 5; SF1) are all east of the main N–S divide (e.g. Fig. 1d), the two most easterly being south of the Grampian divide. These groups account for 52 RSFs, and with ~15 more isolated cases and ~20 in east-side trough-heads within the Clusters, represent ~10% of the Highland population.

In the Lake District, 20/75 RSFs are in such locations, with several others at window breaches into side troughs (Wilson and Jarman, 2015; Fig. 6). In the Southern Uplands, the two remarkably dense and compact local concentrations focus on short isolated glacial troughs (22/37 cases). Dalveen has eight RSFs affecting 0.81km^2, Talla has three, while Moffatdale and its side troughs have eleven totalling 2.79 km^2 (Fig. 7). In Snowdonia, the only three significant RSFs in are in peripheral locations on flanks of sharply-incised trough-

heads (Fig. 15). In mid-Wales, most of the RSF population is within three well-separated trough-head groups (Fig. 8, clusters 3-5).

5.3. Areas of RSF sparsity in the Scottish Highlands

The validity of the CEB:RSF hypothesise can also be tested against the many areas where RSF is sparse (Table 5; SF1; Fig. 5). They occur across all kinds of montane landscape. Sparsity is not surprising on the extensive plateaus (#6M, #12, #14-16) where steep rims and internal valleys are essentially preglacial forms, with CEB localised to occasional breaches or trough-heads (Jarman, 2010b, 2013). But many are on main or secondary (paleo)divides with abundant breaching. Here it has to be inferred that the breaches are relicts of early glacial cycles, with recent erosion rates too low to provoke RSF.

Most perplexing is the ‘terrane link’ paleodivide across Lochaber (Fig. 12), at the maximal ice sheet centre and under moving ice divides. Dense RSF incidence in three parallel paleodivide breaches of contrasting scales in Cluster 3 contrasts with absence both west of the Great Glen (#7G) despite similar intermediate terrain, and in the high Ben Alder and Creag Meagaidh massifs (#5E, #6R) despite apparent major transectional breaches not dissimilar to those in Cluster 4 which support RSF. The long-term evolution of the Spean–Spey catchments (SF5) may explain major eastward migration of the main divide, but not multiple deep gaps in it.

The dense–sparse contrast is most strongly supportive of CEB:RSF where clustering on a perforated main divide gives way to sparsity on main valleysides down-ice. This confirms that they have become ‘stress-hardened’ by long adaptation to ice discharge (SF2.8), whereas the breaches are just recovering from incision and elevated stresses. This is exemplified with the Orchy–Lyon breach nexus (LC3) where the present main Highland watershed is dissected by 6 breaches lined with 17 RSFs, some large. Assuming ice transection mainly eastwards it is notable that RSF is absent on high, steep trough walls on the immediate west (Orchy) side - suggesting longstanding escarpment incisions - and on the east side as soon as the breach zone is left. RSF is virtually absent in Glen Lochay and from upper Glen Lyon, despite their equally high mountains and cross-breaching (Fig. 16).

Glen Lyon then extends narrow and steep-sided for 15 km, beneath high Ben Lawers, with only three modest RSFs, and one in a side trough.

Similar patterns are seen in Cluster 1, where RSF is dense around the divide, in trough-cirques, and on crests, but almost absent on the high walls of Glen Affric (Jarman, 2003c; Fig. 13a); in Cluster 2, where RSFs occur in the perforated Rough Bounds of Knoydart but not eastward down the Quoich-Garry, Kingie, or Arkaig troughs; and at LC2 (Fig. 5), with 14 RSFs around a four-breach nexus, but almost absent down the main walls of Monar, Strathfarrar, Glenuaig, and Strath Conon.

5.4. Coastal cliff RSF - Kintyre, Shetland

This is not included in the montane RSF Inventory, but Britain is noted for its 'high freeboard' (Clayton, 1974) and much of the coast of Scotland is cliffed, often with relief comparable with valleysides. Yet cliff slips and collapses on RSF scale are rare, e.g. one case on the Berwickshire coast (Fig. 7) and one on the north coast.

The remarkable sequence of large, deep-seated RSFs around the Mull of Kintyre (14 sites, 6.58 km^2, one of 2.63 km^2) is thus exceptional, inviting consideration of whether they can be directly attributable to marine erosion - possibly credible for those exposed west to the Atlantic, less so for the lesser cases on the Firth of Clyde side. The alternative is that the promontory (of Dalradian schists, on the paleodivide to N Ireland) has been edge-sharpened by broad icestreams flowing south from Sound of Jura and Firth of Clyde via North Channel to Irish Sea (Finlayson et al., 2014). If sea-level were 100 m lower, these cliffs would be icestream escarpments akin to NW Sutherland (LC1) or the Lake District perimeter.

A supplementary Inventory for Shetland has 28 on diverse lithologies, of which three are large; some are noted on BGS mapping. Ballantyne et al. (2018) identify 128 mainly sub-RSF features, with 13 'deep-seated failures'. Some cliff sites are exposed to the Atlantic or North Sea, but several are on fjords or internal sounds. Again, 'paraglacial' origins in response to ice crossing Shetland (Hall, 2013), with some quasi-breaching selective CEB, might be factored in to complex explanations.

These ‘coastal’ RSF suites might thus be comparable with fjord RSFs in the montane area, as on Loch Long (Fig. 15) and Loch Carron, which just happen to extend to or below sea level.

5.5. West–east transition and climate–landscape interactions

A general spatial pattern emerges of a west–east gradient in both RSF intensity and CEB mode, born of separate paleotectonic and Quaternary climatic factors which have reinforced a positive feedback loop. Thus in the Highlands, the main N-S ice divide has readily become offset inland of the west-centred paleodivide, with thick mobile highly-erosive ice cutting transfluent breaches, whereas further east, thinner more cold-based ice centred over the Grampian divides has had less scope for breaching, instead favouring selective trough development where valleys are deep enough to seed it. This pattern builds on that perceived by Linton (1959) and his west–east zonation of dissection intensity (in Clayton, 1974; SF2.3). Indeed his zones may be migrating eastwards, regionally and locally: indicators such as dogleg breaches and converging trough-heads suggest where they have recently intersected or are close to doing so, aided by the RSFs which line them.

Perhaps the most surprising thing about the CEB:RSF association is that it remains strong after so many Quaternary glacial cycles. Invoking volatile ice centres and discharge patterns (Hubbard et al., 2009; Hughes et al., 2014 - Fig. 10) is attractive, but should have applied in earlier cycles too, diminishing the scope for fresh breaching. Could there be some longer-term climatic evolution sustaining CEB in the west and pushing it east?

One speculative possibility is that intense perforation of the original westerly mountain wall by breaching (Fig. 9A - compare paleo/present divides) has enabled snow-bearing weather systems to penetrate ever further inland. Furthermore, dissection of the west reduces average elevation, increases basal temperatures, and expedites ice discharge, thus diminishing topographic and glaciological support for a west-centred ice sheet. Primary breaching having been accomplished (with many breaches now lacking RSF), second-order breaching has become more braided the further inland the ice divide has migrated. Conversely, increasing snowfall over the eastern plateaux builds more dominant ice caps,

which still being centred over the Grampian divides drive trough excavation rather than breaching.

The Lake District is a microcosm of the Highlands, with its western cluster more breach-related and the easterly more trough-based. The prevailing ice divide locus seems not to be known, but migration north of the main W-E divide would account for its breaching; curiously, RSF paucity south of it suggests late development of both secondary breaches and troughs north of it.

The Southern Uplands also display some W-E transition, but here from glacial to fluvial landsystems, with upland ice cover generally too thin to be erosive. Most RSF is on the steep south side of the asymmetric main divide, which is slowly retreating from the end-Variscan Solway basin. Local clusters imply focussed significant trough enlargement and fluvial incision in the Devensian, for reasons that remain unclear. Yet other glaciated valley segments and steep-sided fluvial valleys show little or no RSF.

Wales is a textbook landscape of glacial erosion, yet RSF is sparse or absent in most higher mountains despite conducive lithologies, while occurring sporadically in lesser hills and fluvial contexts. RSF incidence is only one-sixth that of comparable upland extents in the Highlands, and there are few large sites. Significantly, the Hubbard et al. (2009) model suggests very brief cover by the last BIIS, with outflow to exogenous icestreams either side. There has thus been limited scope for trough enlargement, and no driver to cut breaches through a relatively axial and low-level main watershed (cf. Patton et al., 2012).

6. Discussion - the roles of geology and seismicity

While there is abundant evidence of an association between RSF clusters and late-developing glacial breaches and trough-heads, with a credible cause (CEB), it remains circumstantial and hard to test. It is only envisaged as a partial association (see SF2.7). Having dismissed generic explanations for RSF incidence, the CEB:RSF hypothesis can now be reviewed against the principal non-generic explanations - geology and seismicity. The key question they have to address is: given that glaciated mountainsides are typically close to

critical thresholds of stability (Watters, 1972; McColl, 2012), why should only a small minority display extant RSF?

6.1. Geology

Engineering geology has long recognised the basic propensity for rockslides or topples to occur where susceptible lithologies are inclined at favourable angles (Hoek and Bray, 1981). In mapping the Holmes (1984) dataset, Ballantyne (1986) noted a 'striking correspondence' with Moinian and Dalradian metasediments ('schists'), where they are glacially dissected, and envisaged sliding favoured on their extensive foliation surfaces. By contrast, granite and Torridonian sandstone display abundant rockfall but sparse RSF. The belief that 'geological structure has exercised a fundamental control' (Ballantyne, 1997) is ingrained and merits reappraisal.

Firstly there is no doubt that RSF is favoured globally on metasediments (Augustinus, 1995). However, these vary greatly in metamorphic grade and in propensity to fail, from micaceous pelites (meta-mudstones) to siliceous psammites (meta-sandstones) and granulites/gneisses. Moreover while RSF often appears to be sliding 'on dip' (foliation surface F), it is as often at right angles to or opposite it (Clough, 1897; Holmes, 1984; Cave and Ballantyne, 2016); it may exploit one or more 'throughgoing discontinuities' (typically joint sets J1-4 are found - Watters, 1972); it may release from a local fault; or it may simply ignore fabric and move in the direction of maximum slope stress, as the four inconclusive geotechnical studies of Beinn Fhada might suggest (Ballantyne and Jarman, 2007). Large complex RSFs probably evolve over zones of deformed and fractured bedrock rather than defined basal surfaces (Braathen et al., 2004; Jarman and Wilson, 2015a,b).

All the Highland RSF clusters and all bar one local concentration are in metasediments (Table 5; SF1), which is the predominant if highly variable montane area lithology. Cluster 5 has markedly pelitic facies, but with (F) often folded and contorted, so that sliding is controlled more by joint sets. Clusters 1 and 2 are more psammitic, less folded, and interleaved with thin pelites and semipelites to lubricate mass movement. Cluster 4 has an alternation of quartzites and (semi)pelites, with RSF on both. Metamorphic grade has little

influence, but pressure-metamorphism could be more conducive than heat-metamorphism. RSF occurs freely on near-vertical structures in Clusters 1-2 - notably 'Cluanie deformations' (Jarman, 2006, 2007a), steep structures in Clusters 3-4, inclined structures in Clusters 5/7, and flatter-lying structures in Clusters 6/8. Only local concentration 8 is mainly on granite.

The real test is whether geology can account for areas of notable RSF sparsity (Fig. 5). However, most are wholly or partly on metasediments (Table 5; SF1 and SF2.3), with only those in the NW Highlands on Torridonian sandstone and Lewisian gneiss showing a clear negative geological signal. Some very low massif densities on metasediments (Table 2; SF1) are partly attributable to extensive plateau topography (which could be corrected for by obtaining the extent of slopes >20°). But generally, areas of dense and sparse RSF occur widely on steep high relief and gentler terrain alike.

Thus although geology might account for the near-absence of RSF from the high, dissected Etive and Torridon massifs (#4 granite/#10-11 sandstone), it cannot explain the extreme sparsity on metasediments in rugged mountains such as Creag Meagaidh and Ardgour (#6R, #7S). Although these massifs are predominantly psammitic, RSF clusters occur on the same rocks in Gaick, Glen Roy and around Gulvain. Likewise, structure might seem to influence clustering, as on the Western Highland 'steep beds' constituting the paleodivide spine, with sparsity on the adjacent 'flat beds' of humbler relief; but the steep beds continue south through the #7S area of acute sparsity, despite its breach-dissected steep relief.

In fact RSF does occur locally on tectonised granite, e.g. at Kingairloch and Cluanie. Local concentration 8 in Strath Nethy and other possible quasi-RSFs in the Cairngorm granite breach-passes lack obvious cavities and may be special cases of large-scale rockfall accumulation (Jarman et al., 2013). A few additional landform anomalies posited as RSFs there and on the Skye Red Cuillin granite (Ballantyne et al., 2009; Ballantyne, 2016) may have other origins. Granite being monolithic tends to fail more incrementally by shallow delamination favouring abundant rockfalls. Nevertheless the complete absence of RSF in the deep troughs of the Etive–Cruachan massif (#4) is surprising. Possibly the major 'breaches' dissecting it are older-generation, if not pre-glacial in origin.

In the other ranges, the Lake District exemplifies the secondary relevance of geology, with RSF varying in style but not overall incidence across two contrasting rocktypes (Fig. 6a). Large RSFs occur on both 'Skiddaw Slates' and 'Borrowdale Volcanics', while the two areas of higher density have no apparent geological predisposing factors. Even the small granite intrusions display RSF. In the Southern Uplands (Fig. 7), the contorted sedimentary structure varies little from end-to-end, and the two small clusters have no apparent geological controls. Even the Caledonide Moffatdale Fault is a minor feature, guiding valley orientation more than promoting RSF.

Geology appears most influential in Wales, with smaller-scale RSF on less competent sediments, and absence in the Rhinogs on rugged Cambrian grits. But even here it cannot explain the small clusters. In Snowdonia, the modest incidence has surprised researchers expecting to find RSF on the prevailing resistant volcanic series as commonly as in the geologically not-dissimilar Lake District, which has similarly intense relief dissection among 1000-m peaks. Although 15 sites are mapped here in 'Cluster 1' (Fig. 8), most are small and poorly developed. Few are associated with the passes which dissect Snowdonia, suggesting that these are not true glacial breaches, but old valley systems glacially modified under an independent ice centre (cf. McCarroll and Ballantyne, 2000). The only three significant RSFs are on metasediments fringing the igneous peaks (Fig. 15).

RSF is more abundant in the three Old Red Sandstone massifs and Carboniferous Valleys of southern Wales, but of sedimentary scarp retreat character; and on post-Caledonide terrain beyond the scope of this study.

6.2. Seismicity

Contemporary earthquakes may provoke RSF clusters around them proportionate to their magnitude (Keefer, 1984), but the evidence is mainly from alpine ranges with high tectonic uplift rates and rapid incision; or from emergent orogens where intense RSF is parafluvial and often in very young, incoherent rocks. Even here, "seismic shaking is not a requisite for catastrophic rock slope failure" (Hewitt et al., 2008, p.4). It is notable that extensive studies in the European Alps (Eisbacher and Clague, 1984), Pyrenees (Jarman et al., 2014a), and

Scandes (Böhme et al., 2011) have found very little evidence linking RSF clusters to earthquakes, whether contemporary or pre-historical. Indeed, they commonly ignore seismicity as a significant factor (e.g. Agliardi et al., 2013).

The proposal that earthquakes of the exceptionally high magnitudes required to provoke RSF would have occurred in the Highlands around deglaciation (Fenton, 1991) was later withdrawn, and dismissed as a general explanation in Jarman (2006). 'Enhanced seismic activity' remains advocated as a main factor in Ballantyne et al. (2014). To vindicate it would require (most of) an RSF cluster to be of exactly the same age, or as statistically close to that as dating techniques permit. Even five similar adjacent RSFs on Jura (LC7, Fig. 5) have an age spread of ~1700 years (Ballantyne et al., 2014); their other main proximity groups span 4.3 ka (four Cairngorms granite sites) and 4.8 ka (eight Donegal quartzite sites of which four are within 0.5 ka but a pair on the same hill are 4 ka apart); neighbouring large sites on schist in Cowal date to 1.5 and 3.5 ka BP.

Physical evidence remains lacking: suppposed neotectonic stream offsets (Ringrose, 1989) are 'implausible' (Firth and Stewart, 2000); most of the 'neotectonic fault scarps' of Fenton (1991) are merely differential erosion of weak lineaments; and while soft-sediment disturbances and anomalous sand layers around Glen Roy may reflect local seismicity on drainage of a proglacial lake (Palmer et al., 2010; Sissons, 2017), the RSFs of Cluster 3 (Fig. 8) are of well-spaced ages (Peacock and Cornish, 1989), belying attribution to a single high-magnitude event. In Norway, reported neotectonic features (Stewart et al., 2000) and assumed seismic triggering of large RSFs are now both refuted (Redfield and Hermanns, 2016). In Finland, 89 landslides cluster along postglacial faults with inferred M_W~7 (Ojala et al., 2019) but are all in glacial till.

If only moderately elevated seismicity around deglaciation is now envisaged, as contributing to rockmass fracturing preparatory to failure (after Prager et al., 2008), it becomes merely another generic factor unable to explain RSF spatial incidence (and is even more difficult to verify). It may well have occurred, but nevertheless about 80% of RSFs retain substantial coherence of fabric. In any case, seismicity falls into the class of triggers rather than

underlying causes - a slope has to have approached thresholds of critical stability for other reasons before shaking can exceed them.

Exceptional earthquakes and thus RSF incidence might logically be associated with major basement faults reactivated by glacio-isostatic rebound. Unfortunately they are usually too closely spaced for regional ‘Keefer distributions’ to be inferred (SF2.4); indeed, in the largest Cluster 5, RSF incidence is densest away from these faults. Yet many areas of RSF sparsity are crossed or flanked by major Caledonide faults (Table 5; SF1), while only one of the local concentrations is. Crucially, troughs and breaches often exploit fault weaknesses, making any apparent fault–RSF association self-correlating.

Three main circumstances do emerge from this review where elevated seismicity could account for RSF incidence, and where CEB is least likely to be a driver:

1. high crests and summits - ‘topographic amplification’ (Murphy, 2006) is convincingly proposed in earthquake-prone ranges to account for shaking and collapse of summits, such as Mount Cook. In the Highlands, several of the highest summits and crests have isolated groups of significant RSFs, including Ben Lawers (Fig. 17a) and An Riabhachan (Fenton, 1991).
2. fault lines - although less than 15% of large Highland RSFs are close to major faults, and most of these can simply be ascribed to valleys exploiting them, a few anomalous localities emerge. For instance in Glen Ample (Jarman, 2007; Fig. 17b), RSF density of 10.3% (Cluster 7) includes the second-largest RSF in the Highlands (2.9 km^2) on modest (740m) Ben Our, and the remarkable Beinn Each RSD (Fig. 1b). Other fault-guided examples exist (Smith et al 2009). In Wales, the Tal-y-llyn fault trough has two RSFs disproportionately large for a minor window breach.
3. upland margins - parts of Clusters 5, 7 and 8, and TH6 (Glen Clova), lie within 20 km of the Highland Boundary Fault (Fig. 5). This is noted for low-level seismicity today, and could have provided a focal plane for large earthquakes in a zone where ice sheets often thinned significantly as they repeatedly advanced into the Lowlands, hence promoting differential glacio-isostatic rebound on a regional scale. The Lake

District has several upland-margin RSFs, possibly fault-related, notably Black Combe on the Coniston Fault (Fig. 6; Wilson and Smith, 2006).

6.3. Primary causes of British montane RSF

This review suggests that, in the Highlands, RSF could be primarily attributed thus:

- 40-50% CEB associated with late-developer glacial breaches
- 20-30% CEB associated with late-developer side-valleys and trough-heads
- 10-20% non-spatial or endemic causes, e.g. paraglacial response, periglacial stress, rockmass deterioration/progressive failure/delayed response, cirque development
- <10% elevated seismicity - where this is a primary or preparatory factor, not merely a trigger, including summit crests and perimeter escarpments
- <5% fluvial/parafluvial contexts

Geology is an important secondary factor, influencing density/sparsity, and local style, but not accounting for overall clustering. In the Lake District, the weighting of CEB locales between breach and side-valley is more even. In the Southern Uplands and Wales, trough-head development predominates.

7. Global comparisons in paraglacial contexts

Globally, spatial studies of RSF incidence in glaciated ranges have been limited (e.g. in Evans et al., 2006). In active orogenic belts, RSF is often endemic on conducive lithologies, as in the Southern Alps (Augustinus, 1995; Korup, 2005); Himalaya (Hewitt et al., 2008); and Carpathians (Pànek et al., 2015). The primary, and endemic, driver of CEB and thus RSF here is rapid tectonic uplift. Incision is often primarily fluvial and RSF thus parafluvial, becoming paraglacial at higher levels in deglaciated troughs. Since their main divides generally rise well above ice sheet limits, glacial breaches are rare.

In the European Alps, an extensive icefield was constrained by topography, with only a handful of glacial breaches across the continental divide, mainly at and east of the Rhône–

Rhine nexus. While RSF is abundant in the breach swarm at the major Nufenenpass and Fernpass breaches (e.g. Prager et al., 2008) and into the head of Vinschgau (Jarman et al., 2011), this association only accounts for a tiny proportion of all Alps RSF activity. Agliardi et al. (2013) show that extensive slope deformation incidence is most associated with intermediate long-term exhumation rates, where valley incision and thus CEB is maximised (thus a 'Goldilocks' rate - counterintuitively, very rapid exhumation can escape bulk incision); geological factors are secondary. More local topographic controls might be detectable in lateral valley RSF concentrations (Pedrazzini et al., 2015), where recent glacial erosion rates have been much greater than in main troughs (Sternai et al., 2013), echoing the secondary British CEB locality in enlarging trough-heads.

In the Pyrenees, RSF is widely studied in the fluvially-dissected sedimentary fringes, but under-reported in the glaciated core (Ortuño et al., 2017). Lebourg et al. (2014) map a site within a cluster in the Gave de Pau sector. RSF is infrequent in the eastern Pyrenees, with Jarman et al. (2014a) suggesting that tectonic forcing has declined to approach dynamic equilibrium. They identify a variant CEB:RSF interaction at trough-head transitions, where cirque glaciers have repeatedly extended down-valley, at rock steps with steeper ice gradients and erosivity (cf. Shuster et al. 2011).

The Scandinavian mountains should bear closer comparison to Britain, as a glaciated Caledonide range, albeit submerged beneath a much larger ice sheet. RSF is mapped as comparably extensive to the Highlands in e.g. Troms (Braathen et al., 2004) and West Norway (Böhme et al., 2011). In the former, the Kåfjord RSF cluster (with absence in adjacent valleys) could be partly associated with ice outflow west across the grain, although the breaches are not large (Jarman, 2009; SF2.21). In the latter, transection from an ice divide displaced east of the paleodivide has long been recognised, identifiable by 'agnor' (fish-hook) valleys of capture (Bonow et al., 2003). Dissection by diffluent or cross-cutting breaching in regionally braided icestreams is often intense, and RSF incidence may shed light on this process. RSF may be scarce in the highest massifs further south because the monolithic, high-strength basement rock is unconducive.

In North America, the continental ice sheet partly covered major ranges, and breaching is evident in some areas (e.g. Riedel et al., 2007). RSF studies have a long pedigree, from Radbruch-Hall et al., (1976), although any regional synthesis is still lacking (John Clague, pers. comm. 2014).

This brief overview suggests that the association of RSF with glacial breaches is unusually marked in Britain, but exceptional in most other ranges (e.g. Southern Alps - SF2.22). This may be because Britain is atypical, with modest relief but high precipitation, in a mid-latitude maritime context with rapidly fluctuating ice sheet extents and dispersal routes (Hubbard et al., 2009). Norway and possibly the Patagonian Andes perhaps offer the best comparisons. Nevertheless the CEB:RSF hypothesis has potential value globally in identifying the primary drivers of mass movement in bedrock, whether glacial, fluvial, or tectonic.

8. Conclusions

1. RSF as defined here occurs widely across every mountain range in Britain, and in every local massif (except a few in Wales). A total population of 1082 sites displays a conventional size distribution (Wood et al. 2014), with a regionally consistent average size of 0.15-0.20 km^2. RSF is found on every important lithology and in an extraordinary diversity of morphological locations and physical expressions. Current and recorded RSF activity and hazard are negligible, this being an essentially relict population of paraglacial origins, grading in the fringes to parafluvial.
2. RSF overall incidence is generally thin, despite being so widely distributed: typically around 1% of the montane area; rarely affecting more than 5% of valley walls in a massif; and often absent from the main valleys. As a high-magnitude low-frequency event-class, it is a decidedly anomalous paleo-process and extant landform.
3. Most RSF occurs within main clusters and local concentrations, with areas of notable sparsity yet similar montane character between them. Cluster densities often exceed 5% of montane area, with local concentrations attaining almost 20%. Yet some Highland massif densities fall as low as 0.1%.
4. Geology and structure do not account for this pronounced clustering. Their influence is secondary. Sparsity and clustering coexist in similar geological and topographic contexts.

High-magnitude seismicity is unsupported by dating evidence or fault proximity, but is not ruled out in some unusual contexts. Generic explanations (oversteepening, debuttressing, water pressure) cannot apply when most main valley sides lack RSF even within clusters. Some other spatial variable is required.

5. A previous study (Jarman, 2006) found a marked association between large-RSF clusters and glacial breaching of paleodivides. It proposed that concentrated erosion of bedrock (CEB) in 'late-developing' breaches incised to hectometric depths had generated excess rebound stresses, augmenting prevailing slope stresses sufficiently to provoke failure. This association is confirmed for the whole population, accounting for 40-50% of Highland RSF incidence. It is also seen in the Lake District, if not in the Southern Uplands or Wales.
6. A second RSF association with inferred 'late-developing' trough-heads and side troughs implies CEB during vigorous conversion from fluvial form. Found mainly in easterly locations, these troughs are spatially complementary to 'late-developing' breaches.
7. This CEB:RSF hypothesis is at present conceptual and only envisaged as a partial explanation of RSF incidence. It could be developed and tested by devising an integrated slope stress model into which CEB rebound can be factored. Confirming it would require Quaternary glaciers to have executed large-scale CEB in breaches and trough-heads, in brief episodes.
8. Simulations of the last glacial cycles portray volatile ice dispersal routes and migratory ice divides which could drive selective breach incision and trough enlargement. RSF incidence could therefore aid model calibration and refinement.
9. Regional climatic shifts over the whole Quaternary could be favouring eastward migration of prevailing ice divides, with positive feedback as divide perforation by RSF-aided breaching increases.
10. Although RSF is found in most mountain ranges globally, the strong association with glacial breaching appears almost unique to the Highlands, with only sporadic instances in e.g. Norway and the Alps. This could reflect Britain's marginal climatic position and asymmetric tectonic evolution. Nonetheless, the CEB:RSF hypothesis is clearly relevant to addressing the enigma of what fundamentally drives mass movement in bedrock.

ACKNOWLEDGEMENTS

We thank Ian Evans (Durham/Suceava) for invaluable critiques of the first and final drafts; Graham Holmes, Alun Hubbard, Anna Hughes and the late Brian Sissons for permission to utilise material from their models and surveys; and many colleagues at BGS Edinburgh and Nottingham for much assistance. Many of these ideas were honed on the hill with Peter Wilson, Richard Scothorne, Eva Sahlin, Niall Petch, Fionn Petch, Douglas Peacock, Wishart Mitchell, Jon Merritt, Sven Lukas, Martin Kirkbride, Catherine Inglis, Adrian Hall, John Gordon, Dave Evans, Ben Chandler, Clare Boston and Colin Ballantyne. Several anonymous reviews have been valuable and supportive. The first author is indebted to the second for rescuing this paper from desuetude.

Figure Captions

Fig. 1. Rock Slope Failure characterisation. a) Simple schema found applicable to many mountain areas. b) Rock Slope Deformation - Beinn Each, Southern Highlands north of Callander. c) Rockslide - Meall na Dige, Southern Highlands north of Balqhuidder, progressing from 1 - RSD via 2 - arrested translational slide to 3 - sub-cataclasmic debris slumps (supported by Younger Dryas cirque glacier?). c) Rock avalanche - Loch a' Bhealaich, Ben Klibreck, Northern Highlands, extensional RSD progressing to disintegration and sub-cataclasmic collapse with spray fan. All sites on metasediments.

Fig. 2. Mountains ranges of Britain in pre-Devonian rocks, relicts of the Cambro-Silurian Caledonian orogeny. Terranes 1 and 2 comprise the Scottish Highlands, terranes 5 and 6 the Welsh mountains.

Fig. 3. Probabilistic RSF rating: 'definite' RSFs are evident on imagery from snow traces/shadow lines, both in trough-head angles and on the open south face. Site #10 is only rated 'possible' : although distinctly anomalous, with an apparent source shape and concavo-convex form, it lacks clear RSF indicators or on-site 'feel'and may be a 'fossil' RSF from an earlier cycle. Site #11 (Aonach air Chrith) was rated 'probable' as a good candidate with sharp lineaments, groundtruthing since uprates to 'definite' deformation in bedrock, not erosional or glacial cover. Site #12 (Druim Shionnach) is type example of the 'Cluanie Deformation' (Jarman, 2007a) developed on sub-vertical schists, but with outer extent diffuse, thus only 'probable'. These RSFs are in Cluster 1 (Fig. 4). a) Image © Google Earth. b) photo from north into hanging side-trough above major Glen Shiel glacial breach - left side now 'definite', right side 'possible'.

Fig. 4. RSF size distribution - Scottish Highlands September 2018, n=920. The long tail is compressed (largest sites are 2.90 and 3.00 km^2). Entry-level sites (0.01 km^2) are still under-represented.

Fig. 5. RSF clusters in the Scottish Highlands, with large RSFs (>0.25 km^2) plotted. Local concentrations in breach and trough-head contexts are numbered, as are main areas of sparsity. Mountain areas (white) exclude broader tracts of lower relief: their perimeters rise from sea level in the west to ~600 m asl in the east. The paleic summit surface is mainly between 800-1200 m asl. It is heavily dissected in the west, but only selectively in the east. The Paleogene igneous province is excluded from the Inventory. Present watersheds are often displaced from inferred preglacial paleodivides by up to 20 km. (updated from Jarman, 2006).

Fig. 6. English Lake District - range 4 in Fig. 2. a) RSF 2018 data, all sizes - widely distributed across contrasting lithologies, but with extensive sparsity, notably in central areas of glacial scouring and on main valley sides. b) Kirk Fell RSF (Wilson, 2005) - RSD slicing a plateau-summit and upper flanks, between window breaches from Ennerdale (behind) across the main W-E divide (view NNE from Illgill Head).

Fig. 7. Southern Uplands of Scotland - range 3 in Fig. 2. Large areas are devoid of RSF, including the high, glacially-dissected Galloway hills. The two central RSF concentrations associate with short glacial troughs and adjacent glacifluvial incisions. The Langholm and Kale Water (Cheviot) clusters are beyond the Inventory area, on younger sediments and volcanics.

Fig. 8. Wales - Snowdonia and Cambrian Mountains - ranges 5-6 in Fig. 2. Within general sparsity, modest RSF groupings occur (1) in Snowdonia, (2) around Cadair Idris possibly associated with ice-stream constriction, with a minor breach and deep trough along the Tal-y-llyn Fault, and (3-5) where late-developing trough-heads incise the central plateau.

Fig. 9. Breaching intensity in two 30-km sectors of Highland main divides (Fig. 10), showing (A) maximal perforation of Segment 5 (south), with ~30% of preglacial cross-sectional area above present sea level removed; and (B) breach scale reducing and spacing increasing eastwards along Segment 1, where Loch Ericht breach exploits Fault ELF. Breaches lacking RSF may be early Quaternary (eg. Drumochter) or pre-Quaternary throughways (eg. Quoich-Hourn). Only RSFs in breaches shown, others may occur within a few km down-valley.

Fig. 10. Ice divide (iceshed) migration of 100 km amplitude across the Scottish Highlands, extracted with approval from a ten-Stage reconstruction of the last British Ice Sheet by Hughes et al., (2014, their Fig. 8). This now confirms (i) displacement of the main iceshed at maxima well to the east of the main Highland watershed (dotted), thus driving glacial breaching west to the Atlantic, (ii) large-scale oscillation of the iceshed and its branches, especially during downwasting, thus generating see-saw incision, and (iii) cross-cutting ice flows contributing to areal dissection, notably SW Highlands (Fig. 14). Selected main breaches and enlarged through valleys are attributed to Stages most aligned with them (many are aligned with several Stages, not all can be shown). Nearly all breaches can be accounted for. Stage 2 (not mapped) is similar to 5/7north, Stage 6north (not mapped) is similar to 8north but takes an even more extreme displacement east of Inverness.

Fig. 11. Highland paleodivides: the present main watersheds (dotted) are descended from post-Caledonian protodivides, of which:

- some have remained axial and relatively fixed (Segments 1-2),
- others have become asymmetric and have displaced progressively eastwards in response to post-Variscan basin tectonics and Quaternary breaching (Segments 4-6, locations more conjectural);
- Segments 4-5N-7-6 comprise the Main Highland Paleodivide (Atlantic–North Sea); positions shown are time-transgressive from (pre-)Paleogene to Pliocene (the ‘preglacial divides’ reconstructed on Fig. 5 are their inferred latest evolution);
- doglegs across major Caledonide faults are suggestive of lateral strike-slip, mainly sinistral; alternative positions for them are possible;
- the inter-terrane link (7) is shown crossing the Great Glen close to the present watershed (Fig. 12), but could originally have been further south.

Pre-Caledonide basement is exposed west of the Moine Thrust front, which has retreated east; rest of mountain area comprises Precambrian metasediments with Caledonide fold/thrust structures and igneous intrusions. See SF5 for fuller discussion.

Fig. 12. Paleodivides, glacial breaches, drainage reversals, and RSF clustering/sparsity contrasts in the Lochaber–Badenoch nexus (location - Fig. 5). a) Present main Highland and Grampian watersheds meet near Ben Alder, displaced east by long-term invasion of east-side Spey/Tay headwaters by the west-coast Linnhe/Spean system, and additionally by glacial transfluence. Glacial breaches of the main paleodivides respond to transfluence patterns (Fig. 10). Captured Spey headwaters are highlighted with ‘agnor’ hooks. b) Doorway and window breaches through the Lochaber paleodivide (per Linton, 1949), Loch Treig displaying CEB of ~600 m below the inferred paleo-col, cross-sectional area 1.4 km^2. View north from Leum Uilleim - pont 906 on a).

Fig. 13. Major breaches in Cluster 1, Western Highlands (location - Fig. 5). a) densest RSF occurs where the main divide has been displaced ~5/7 km east in Glens Shiel and Lichd. Breaches have been cut by mainly westward but possibly some eastward transfluence (Fig. 10), with CEB of 600-800 m at the reconstructed paleodivide cols. Proto-valleyheads were steep to the west coast and shallow to the east. Drainage has been reversed, with major RSDs in this zone of maximum disturbance. Note only isolated RSFs on main valleysides away from breaches. b) transfluent 'window' and 'doorway' breaches of the secondary Cluanie–Affric divide are lined with RSF, probable ice flow directions NW and NE, view north from Creag a' Mhaim.

Fig. 14. Intense glacial dissection by a 'braided' breaching network in the SW Highlands. Cluster 5 - Cowal-Arrochar-Luss is the largest in the British mountains. Major RSFs associate with transectional and 'fjord' breaches, and smaller-scale RSFs with the higher-level 'window' breach network. Local RSF concentrations west of Loch Eck (LC5) and around Balquhidder Glen (LC4) are markedly related to cross-breaches of secondary divides. RSF is sparse away from breaches, in main valleys long adapted to ice discharge. RSF incidence is poorly associated with the major Caledonide faults, except where these have been locally exploited by breach-troughs, e.g. RBT pass.

Fig. 15. Major RSFs on trough-head flanks in Snowdonia - locations on Fig. 8:
a) #W05 MC - Moel Cynghorion NW of Snowdon, rim slipped by 5-10 m above probable residual debris mass in 'cirque', majority glacially exported;
b) #W13 PH - Pen yr Helgi-du, arrested translational slide RSF lowered ~120 m, ice-supported/trimmed;
c) #W15 MM - Moelwyn Mawr, sub-cataclasmic rock avalanche, reinterpreted from rock glacier (Jarman et al., 2013); possible rare neotectonic scarp on right.

Fig. 16. Density>sparsity contrasts in LC3 Orchy–Lyon. a) High RSF incidence at an inferred late-developing breach nexus on the main Southern Highland watershed, contrasting with near-absence in main glens east and west, despite comparable relief; basemap © Microsoft. b) RSFs on Beinn a' Chreachain, on the flank of a breached trough-head, with debris partly removed by glaciers. c) the remarkable 'slipped disc' RSF at 'Coire' Chirdle, above the corkscrew Orchy–Lyon breach; the faint incipient deformation on Meall Tionail (upper left) remains only 'possible' despite groundtruthing; image © Bing Maps.

Fig. 17. Seismicity could have a local role: a) where high summits have multiple RSFs, with topographic amplification of moderate-magnitude events, here on Ben Lawers, Southern Highlands above Loch Tay, with slumped masses breaking a former domed crest, and incipient slips with source fractures marked; or b) where a minor valley follows a Caledonide Fault adjacent to the Highland Boundary Fault (Beinn Each RSF shown in Fig. 1b). Photo (a) John Digney, basemap (b) © Microsoft.

REFERENCES

Agliardi, F., Crosta, G.B., Frattini, P. ,Malusà, M.G., 2013. Giant non-catastrophic landslides and the long-term exhumation of the European Alps. Earth and Planetary Science Letters 365, 263–274.

Allaby, A., Allaby, M., 1990. Dictionary of Earth Sciences. Oxford University Press, Oxford. 619 pp.

Allen, S.K., Cox, S.C., Owens, I.F., 2011. Rock avalanches and other landslides in the central Southern Alps of New Zealand: a regional study considering possible climate change impacts. Landslides 8, 33-48.

Augustinus, P.C., 1995. Rock mass strength and the stability of some glacial valley slopes. Zeitschrift für Geomorphologie 39, 55–68.

Bailey, E.B., Maufe, H.B.,1916. Geology of Ben Nevis and Glencoe. Explanation of Sheet 53. Memoirs of the Geological Survey, Edinburgh.

Ballantyne, C.K., 1986. Landslides and slope failures in Scotland: a review. Scottish Geographical Magazine 102, 134-150.

Ballantyne, C.K., 1997. Holocene rock-slope failures in the Scottish Highlands. In Matthews, J.A. (Ed.), Rapid mass movement as a source of climatic evidence for the Holocene. Paleoklimaforschung, 19, pp., 197-205.

Ballantyne, C.K., 2002. Paraglacial geomorphology. Quaternary Science Reviews 21, 1935–2017.

Ballantyne, C.K. 2007a. Trotternish Escarpment, Isle of Skype. In: Cooper, R.G. (Ed.), Mass Movements in Great Britain. Geological Conservation Review Series 33, JNCC, Peterborough, 196-204.

Ballantyne, C.K., 2007b. Beinn Alligin. In: Cooper, R.G. (Ed.), Mass Movements in Great Britain. Geological Conservation Review Series 33, JNCC, Peterborough, pp. 111-116.

Ballantyne, C.K., 2013. Lateglacial rock-slope failures in the Scottish Highlands. Scottish Geographical Journal 129, 67-84.

Ballantyne, C.K., 2018. Glacially moulded landslide runout debris in the Scottish Highlands. Scottish Geographical Journal 134, 224-236.

Ballantyne, C.K., Jarman, D., 2007. Beinn Fhada (Ben Attow). In: Cooper, R.G. (Ed.), Mass Movements in Great Britain. Geological Conservation Review Series 33, JNCC, Peterborough, pp. 56-62.

Ballantyne, C.K., 2016. Rock slope failures on Skye. In: Ballantyne, C.K., Lowe, J.J., The Quaternary of Skye - Field Guide. Quaternary Research Association, London, pp. 77-88.

Ballantyne, C.K., Schnabel, C., Xu, S., 2009. Exposure dating and reinterpretation of coarse debris accumulations ('rock glaciers') in the Cairngorm Mountains, Scotland. Journal of Quaternary Science 24, 19-31.

Ballantyne, C.K., Wilson, P., Gheorghiu, D., Rodés, Á., 2014. Enhanced rock-slope failure following ice-sheet deglaciation: timing and causes. Earth Surface Processes and Landforms 39, 900-913.

Ballantyne, C.K., Dawson, S., Dick, R., Fabel, D., Kralikaite, E., Milne, F., Sandeman, G.F., Xu, S., 2018. The coastal landslides of Shetland. Scottish Geographical Journal, DOI: 10.1080/14702541.2018.1457169

Beget, J.E., 1985. Tephrochronology of antislope scarps on an alpine ridge near Glacier Peak, Washington, U.S.A. Arctic and Alpine Research 17, 143–152.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and glaciation. Arnold, London, 734pp.

Blikra, L.H., Longva, O., Braathen, A., Anda, E., Dehls, J.F., Stalsberg, K., 2006. Rock slope failures in
Norwegian fjord areas: examples, spatial distribution and temporal pattern. In: S. Evans, G. Mugnozza, A. Strom, R. Hermanns (Eds.), Landslides from Massive Rock Slope Failure. NATO

Science Series. Springer Netherlands, pp. 475-496.

Blikra, L.H., Kristensen, L., Lovisolo, M., 2012. Subsurface monitoring of large rockslides in Norway: a key requirement for early warning. Italian Journal of Engineering Geology and Environment - Book Series 6, 307-314.

Blondeau, S., 2018. Ruptures de Versant Rocheux (RVR) à l'échelle des Alpes occidentales : inventaire systématique, analyse spatiale, perspectives patrimoniales. PhD thesis, University of Lyon.

Böhme, M., Saintot, A., Henderson, I., Henriksen, H., Hermanns, R.L., 2011. Rock-slope instabilities in Sogn and Fjordane County, Norway: a detailed structural and geomorphological analysis. In: Jaboyedoff, M. (Ed.), Slope Tectonics. Geological Society London, Special Publication 351, pp. 97-111.

Bonow, J.M., Lidmar-Bergström, K., Näslund, J-O., 2003. Palaeosurfaces and major valleys in the area of the Kjølen Mountains, southern Norway – consequences of uplift and climatic change. Norsk Geografisk Tidsskrift 57, 83–101.

Boston, C.M., Carr, S.J., Lukas, S., 2015. A Younger Dryas plateau icefield in the Monadhliath, Scotland, and implications for regional palaeoclimate. Quaternary Science Reviews 108, 139-162.

Braathen, A., Blikra, L.H., Berg, S.S., Karlsen, F., 2004. Rock-slope failures in Norway; type, geometry and hazard. Norwegian Journal of Geology 84, 67-88.

Bradwell, T., Stoker, M., Krabbendam, M., 2008. Megagrooves and streamlined bedrock in NW Scotland: the role of ice streams in landscape evolution. Geomorphology 97, 135-156.

Brardinoni, F., Slaymaker, O., Hassan, M.A., 2003. Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. Geomorphology 54, 179-196.

British Geological Survey, 1987. 1:50,000 Sheet 38W Ben Lomond - landslides inset map.

Carter, G., 2015. Rock avalanche scars in the geological record: an example from Little Loch Broom, NW Scotland. Proceedings of the Geologists' Association 126, 698–711.

Cave, J.A.S., Ballantyne, C.K., 2016. Catastrophic Rock Slope Failures in NW Scotland: quantitative analysis and implications. Scottish Geographical Journal 132, 185-209.

Clague, J.J.,Stead, D. (Eds.), 2012. Landslides; types, mechanisms and modeling. Cambridge University Press, Cambridge, UK. 420 pp.

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C.J., Sejrup, H.P., 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. Quaternary Science Reviews 44, 112-146.

Clayton, K.M., 1974. Zones of glacial erosion. Institute of British Geographers Special Publication 7, 163-176 (includes unpublished material by D.L. Linton).

Clough, C.T., 1897. Landslips. In: Gunn, W., Clough, C.T., Hill, J.B. (Eds.). The geology of Cowal. Memoirs of the Geological Survey, Edinburgh.

Cossart, E., Mercier, D., Decaulne, A., Feuillet, T., Jónsson, H.P., Sæmundsson, Þ., 2013. Impacts of post-glacial rebound on landslide spatial distribution at a regional scale in Northern Iceland (Skagafjörður). Earth Surface Processes and Landforms 39, 336-350.

Crosta, G.B. and Clague, J.J., 2006. Large landslides: dating, triggering, modelling, and hazard assessment. Engineering Geology 83, 1-3.

Crosta, G.B., Frattini, P., Agliardi, F., 2013. Deep seated gravitational slope deformations in the European Alps. Tectonophysics 605, 13–33.

Dashwood, C., Pennington, C., Bee, E., Freeborough, K., Dijkstra, T., 2017. Creation of a National Landslide Domain Map to Aid Susceptibility Mapping in Great Britain. In: Mikoš, M. et al. (eds.), Advancing Culture of Living with Landslides. Springer, Dordrecht.

DoE, 1993. Landslides inventory for Great Britain (county/region lists). Unpublished compilation by Geomorphological Services Ltd for Department of the Environment, London.

Dury, G.H., 1953. A glacial breach in the north-western Highlands. Scottish Geographical Magazine 69, 106-17.

Eeckhaut, M. van den, Hervás, J., 2012. State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk. Geomorphology 139, 545–558.

Egholm, D.L., Pedersen, V.K., Knudsen, M.F., Larsen, N.K., 2012. Coupling the flow of ice, water, and sediment in a glacial landscape evolution model. Geomorphology 141, 47-66.

Eisbacher, G.H., Clague, J.J., 1984. Destructive mass movements in high mountains: hazard and management. Geological Survey of Canada Professional Paper 84:16.

Evans, I.S., 1997. Process and form in the erosion of glaciated mountains. In: Stoddart, D.R. (Ed.), Process and form in geomorphology. Routledge, London, 145–174.

Evans, S.G., Scarascia Mugnozza, G., Strom, A., Hermanns, R. (Eds.), 2006. Landslides from massive rock slope failure. Springer, Dordrecht. 662 pp.

Fenton, C.H., 1991. Neotectonics and paleoseismicity in NW Scotland. Ph.D. thesis, University of Glasgow.

Finlayson, A., Fabel, D., Bradwell, T., Sugden, D., 2014. Growth and decay of a marine terminating sector of the last British Irish Ice Sheet. Quaternary Science Reviews 83, 28-45.

Firth, C.R., Stewart, I.S., 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. Quaternary Science Reviews, 19, 1469-1493.

Foster, C., Pennington, C.V.L., Culshaw, M.G., Lawrie, K., 2012. The National Landslide Database of Great Britain: development, evolution and applications. Environmental Earth Sciences 66, 941-953.

Glasser, N.F., 1995. Modelling the effect of topography on ice sheet erosion, Scotland. Geografiska Annaler 77A, 67-82.

Godard, A., 1965. Recherches de Géomorphologie en Écosse du Nord-Ouest. Université de Strasbourg, Publications de la Faculté des Lettres, Fondation Baulig.

Goudie, A.S., (Ed.), 2004. Encyclopedia of Geomorphology. Routledge, London. 1184 pp.

Grämiger, L.M., Moore, J.R., Gischig, V.S., Ivy-Ochs, S. ,Loew, S., 2017. Beyond debuttressing: mechanics of paraglacial rock slope damage during repeat glacial cycles. Journal of Geophysical Research: Earth Surface 122,1004-1036.

Grämiger, L. M., Moore, J. R., Gischig, V. S., Loew, S., 2018. Thermomechanical stresses drive damage of Alpine valley rock walls during repeat glacial cycles. Journal of Geophysical Research: Earth Surface, 123. https://doi.org/10.1029/2018JF004626

Hall, A.M., 1991. Pre-Quaternary landscape evolution in the Scottish Highlands. Transactions of the Royal Society of Edinburgh: Earth Sciences 82, 1-26.

Hall, A. M., 2013. The last glaciation of Shetland: Local ice cap or invasive ice sheet? Norwegian Journal of Geology 93, 229–242.

Harrison, S., 1999. The problem with landscape: some philosophical and practical questions. Geography: Journal of the Geographical Association, 84(4), 355-363.

Harrison, S., Glasser, N., Anderson, E., Ivy-Ochs, S., Kubik, P.W., 2010. Late Pleistocene mountain glacier response to North Atlantic climate change in southwest Ireland. Quaternary Science Reviews, 29, 3948-3955.

Haynes, V.M., 1977. The modification of valley patterns by ice sheet activity. Geografiska Annaler 59A, 195-207.

Hewitt, K., Clague, J.J., Orwin, J.F., 2008. Legacies of catastrophic rock slope failures in mountain landscapes. Earth Science Reviews 87, 1-38.

Hoek, E., Bray, J.W., 1981. Rock slope engineering, 3rd Edition. Inst. of Mining and Metallurgy, London.

Holmes, G., 1984. Rock-slope failure in parts of the Scottish Highlands. Ph.D. thesis, University of Edinburgh (available online).

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. Quaternary Science Reviews 28, 758-776.

Hughes, A.L.C., Clark, C.D., Jordan, C.J., 2014. Flow-pattern evolution of the last British Ice Sheet. Quaternary Science Reviews 89, 148-168.

Hungr, O., Leroueil, S., Picarelli, L., 2014. The Varnes classification of landslide types, an update. Landslides 11, 169-194.

Hurst, M. D., Ellis, M. A., Royse, K. R., Lee, K. A., Freeborough, K., 2013. Controls on the magnitude-frequency scaling of an inventory of secular landslides. Earth Surface Dynamics 1, 67-78.

Hutchinson, J.N., 1988. General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. Proceedings 5th Int. Symposium on Landslides, Lausanne, vol. 1. Balkema, Rotterdam, 3-35.

Hutchinson, J.N., 2006. Massive rock slope failure: perspectives and retrospectives on the state-of-the-art. In: Evans, S.G., Scarascia Mugnozza, G., Strom, A., Hermanns, R. (Eds.), Landslides from massive rock slope failure. Springer, Dordrecht, pp. 619-662.

Hutchinson, J.N., Millar, D.L., 2001. The Graig Goch landslide dam, Meirionnydd, mid Wales. In: Walker, M.J.C., McCarroll, D. (Eds.), The Quaternary of West Wales: Field Guide. Quaternary Research Association, London, pp. 113-125.

Jarman, D., 2003a. Paraglacial landscape evolution – the significance of rock slope failure. In: Evans, D.J.A., (Ed.), The Quaternary of the Western Highland Boundary – Field Guide. Quaternary Research Association, London, pp. 50-68.

Jarman, D., 2003b. The Glen Shiel rock slope failure cluster. In: Tipping, R., (Ed.), The Quaternary of Glen Affric and Kintail - Field Guide. Quaternary Research Association, London, pp. 165-183.

Jarman, D., 2003c. The An Sornach rock slope failure. In: Tipping, R. (Ed.). Glen Affric and Glen Shiel – Field Guide. Quaternary Research Association, London, 63-74.

Jarman, D., 2004. Rock slope failures of the Gaick Pass. In: Lukas, S., Merritt, J.W., Mitchell, W. (Eds.), The Central Grampian Highlands – Field Guide. Quaternary Research Association, London, pp. 103-111.

Jarman, D., 2006. Large rock slope failures in the Highlands of Scotland: characterisation, causes and spatial distribution. Engineering Geology 83, 161–182.

Jarman, D., 2007. Introduction to the mass movements in the older mountain areas of Britain (with site reports). In: Cooper, R.G. (Ed.), Mass Movements in Great Britain. Geological Conservation Review Series 33, JNCC, Peterborough, pp. 33-55.

Jarman, D., 2008. The Roy-Lochy rock slope failure cluster: implications for glacial breaching, ice movements, and Parallel Road dislocations. In: Lowe, J.J., Rose, J., Palmer, A. (Eds.), The Quaternary of Glen Roy and vicinity – Field Guide. Quaternary Research Association, London, pp. 98–104.

Jarman, D., 2009. Paraglacial rock slope failure as an agent of glacial trough widening. In: Knight, J., Harrison, S. (Eds.), Periglacial and paraglacial processes and environments. Geological Society of London Special Publication 320, 103–131.

Jarman, D., 2010a. Anomalous deposits and landforms in the Welsh mountains - problems of rock slope failure interpretation. Quaternary Newsletter 122, 1-15.

Jarman, D., 2010b. Rock slope failure in NW Sutherland, with landscape evolution and Meall a' Chleirich sub-cataclasmic RSF complex. In: Lukas, S, Bradwell, T., (Eds.), The Quaternary of Western Sutherland and adjacent areas – Field Guide. Quaternary Research Association, London, pp. 13-28, 73-81, 213-219.

Jarman, D., 2013. Rock Slope Failure sparsity in the Monadhliath Mountains, with landscape evolution and Glen Killin rock slope failure mini-cluster. In: Boston, C.M., Lukas, S., Merritt, J.W. (Eds.), The Quaternary of the Monadhliath and the Great Glen – Field Guide. Quaternary Research Association, London, pp. 9-24, 59-71, 129-134.

Jarman, D., Agliardi, F., Crosta, G., 2011. Megafans and outsize fans from catastrophic slope failures in alpine glacial troughs: the Malser Haide and the Val Venosta cluster, Italy. In: Jaboyedoff, M. (ed.), Slope Tectonics. Geological Society of London Special Publication 351, 253-278.

Jarman, D., Wilson, P., 2015a. Anomalous terrain at Dove Crags cirque–Gasgale Gill, English Lake District, interpreted as a large pre-LGM rock slope failure complex. Proc eedings of the Yorkshire Geological Society 60, 243-257.

Jarman, D., Wilson, P., 2015b. Clough Head—Threlkeld Knotts: a perplexing RSF complex. In: McDougall, D.A., Evans, D.J.A. (Eds.), The Quaternary of the Lake District – Field Guide. Quaternary Research Association, London, pp. 153-173.

Jarman, D., Wilson, P., Harrison, S., 2013. Are there any relict rock glaciers in Britain? Journal of Quaternary Science 28, 131–143.

Jarman, D., Calvet, M., Corominas, J., Delmas, M., Gunnell, Y., 2014a. Large-scale rock slope failures in the eastern Pyrenees: identifying a sparse but significant population in paraglacial and parafluvial contexts. Geografiska Annaler 96A, 357-391. Online Supporting Information includes SI-07 The 'parafluvial RSF' concept, 6 pp.

Jarman, D., McColl, S., Cook, S., Hoon, S., 2014b. Can valley rebound after concentrated erosion of bedrock drive montane rock slope failure? The Glen Roy (Scotland) geodetic datum. Abstracts volume - 3rd Slope Tectonics Conference, 8–12 September 2014, Trondheim, Norway.

Keefer, D.K., 1984. Landslides caused by earthquakes. Geological Society of America Bulletin 95, 406–421.

Knight, J., Harrison, S., 2013. The impacts of climate change on terrestrial Earth surface systems. Nature Climate Change *3*, 24.

Korup, O., 2005. Distribution of landslides in SW New Zealand. Landslides 2, 43-51.

Korup, O., Clague, J.J., Hermanns, R.L., Hewitt, K., Strom, A.L., Weidinger, J.T., 2007. Giant landslides, topography, and erosion. Earth and Planetary Science Letters, 261(, 578-589.

Lebourg, T., Zerathe, S., Fabre, R., Giuliano, J., Vidal, M., 2014. A Late Holocene deep-seated landslide in the northern French Pyrenees. Geomorphology, 208, 1-10.

Linton, D.L., 1949. Watershed breaching by ice in Scotland. Transactions of the Institute of British Geographers 15, 1-16.

Linton, D.L., 1959. Morphological contrasts between eastern and western Scotland. In: Miller, R., Watson, J.W. (Eds.), Geographical essays in memory of Alan G. Ogilvie. Nelson, Edinburgh, pp. 16-45.

Macdonald D., Archer B., Murray S., Smith K., Bates A., 2007. Modelling and comparing the Caledonian and Permo-Triassic erosion surfaces with present-day topography across Highland Scotland: implications for landscape inheritance. In: Nichols, G., Williams, E., Paola, C. (Eds.): Sedimentary processes, environments and basins. A tribute to Peter Friend. Blackwell, Oxford. pp.1-16.

Matheson, D.S., Thomson, S., 1973. Geological implications of valley rebound. Canadian Journal of Earth Sciences 10, 961-978.

McCarroll, D., Ballantyne, C.K., 2000. The last ice sheet in Snowdonia. Journal of Quaternary Science 15, 765-778.

McColl, S.T., 2012. Paraglacial rock-slope stability. Geomorphology 153, 1–16.

Mercier, D., Coquin, J., Thierry, F., Deculne, A., Cossart, E., Jónsson, H.P., Sæmundsson, B., 2017. Are Icelandic rock-slope failures paraglacial? Age evaluation of seventeen rock-slope failures in the Skagafjörður area, based on geomorphological stacking, radiocarbon dating and
tephrochronology. Geomorphology 296, 45–58.

Murphy, W., 2006. The role of topographic amplification on the initiation of rock slopes failures during earthquakes. In: S. Evans, G. Mugnozza, A. Strom, R. Hermanns (Eds.), Landslides from Massive Rock Slope Failure. NATO Science Series. Springer Netherlands, pp. 139-154.

Ojala, A.E.K., Mattila J., Markovaara-Koivisto , M., Ruskeeniemi , T., Palmu, J-P., Sutinen, R., 2019.
Distribution and morphology of landslides in northern Finland: An analysis of postglacial seismic activity. Geomorphology 326, 190-201.

Ortuño, M., Guinau, M., Calvet, J., Furdada, G., Bordonau, J., Ruiz, A., Camafort, M., 2017. Potential of airborne LiDAR data analysis to detect subtle landforms of slope failure: Portainé, Central Pyrenees. Geomorphology 295, 364–382.

Palmer, A.P., Rose, J., Lowe, J.J., MacLeod, A., 2010. Annually-resolved events of Younger Dryas glaciation in Lochaber (Glen Roy and Glen Spean), Western Scottish Highlands. Journal of Quaternary Science 25, 581–596.

Pànek, T., Klimes, J., 2015. Temporal behaviour of deep-seated gravitational slope deformations: a review. Earth-Science Reviews 156, 14-38.

Pànek, T., Mentlík, P., Ditchburn, B., Zondervan, A., Norton, K., Hradecký, J., 2015. Are sackungen diagnostic features of (de)glaciated mountains? Geomorphology 248, 396–410.

Pànek, T., Lenart, J., Hradecký, J., Hercman, H., Braucher, R.,Silhàn, K., Skarpich, V., 2018. Coastal cliffs, rock-slope failures and Late Quaternary transgressions of the Black Sea along southern Crimea. Quaternary Science Reviews 181, 76–92.

Patton, H., Hubbard, A., Glasser, N., Bradwell, T., Golledge, N., 2012. The last glacial cycle in Wales: Part 2 - dynamics of a topographically-controlled ice cap. Boreas 42, 491-510.

Peacock, J.D., Cornish, R. (Eds.), 1989. Glen Roy area - Field Guide. Quaternary Research Association, Cambridge.

Peacock, J.D., Mendum, J.R., Fettes, D.J., 1992. Geology of the Glen Affric District. Memoir for 1:50,000 geological sheet 72E. HMSO, London.

Pedrazzini, A., Humair, F., Jaboyedoff, M., Tonini, M., 2016. Characterisation and spatial distribution of gravitational slope deformation in the Upper Rhône catchment (Western Swiss Alps). Landslides 13, 259-277.

Peras, A., Decaulne, A., Cossart, E., Coquin, J., Mercier, D., 2016. Distribution and spatial analysis of rockslides failures in the Icelandic Westfjords: first results. Géomorphologie 22, 25-35.

Persaud, M., Pfiffner, O.A., 2004. Active deformation in the eastern Swiss Alps: post-glacial faults, seismicity and surface uplift. Tectonophysics 385, 59-84.

Prager, C., Zangerl, C., Patzelt, G., Brandner, R., 2008. Age distribution of fossil landslides in the Tyrol (Austria) and its surrounding areas. Natural Hazards and Earth Systems Science 8, 377-407.

Radbruch-Hall, D.H., Varnes, D.J., Savage, W.Z., 1976. Gravitational spreading of steep-sided ridges ("sackung") in western United States. Bulletin of the International Associationof Engineering Geology 14, 23-35.

Redfield, T.F., Hermanns, R.L., 2016. Gravitational slope deformation, not neotectonics: Revisiting the Nordmannvikdalen feature of northern Norway. Norwegian Journal of Geology 96, 1–29.

Riedel, J.L., Haugerud, R.A., Clague, J.J., 2007. Geomorphology of a Cordilleran Ice Sheet drainage network through breached divides in the North Cascades Mountains of Washington and British Columbia. Geomorphology 91, 1-18.

Ringrose, P.S., 1989. Recent fault movement and palaeoseismicity in western Scotland. Tectonophysics 163, 305-314.

Rowan, A.V., Plummer, M.A., Brocklehurst, S.H., Jones, M.A., Schulz, D.M., 2013. Drainage capture and discharge variations driven by glaciation in the Southern Alps, New Zealand. Geology 41, 199-202

Rudberg, S., 1992. Multiple glaciations in Scandinavia – seen in gross morphology or not? Geografiska Annaler 74A, 231-243.

Sharp, M., Dowdeswell, J.A., Gemmell, J.C., 1989. Reconstructing past glacier dynamics and erosion from geomorphic evidence, Snowdon, North Wales. Journal of Quaternary Science 4, 115-130.

Sissons, J.B., 1967. The evolution of Scotland's scenery. Oliver and Boyd, Edinburgh. 259 pp.

Sissons, J.B., 2017. The lateglacial lakes of Glens Roy, Spean and vicinity (Lochaber district, Scottish Highlands). Proceedings of the Geologists' Association 128, 32-41.

Sissons, J.B., Cornish, R., 1982. Differential isostatic uplift of crustal blocks at Glen Roy, Scotland. Quaternary Research 18, 268-88.

Shuster, D.L., Cuffey, K.M., Sanders, J.W., Balco, G., 2011.Thermochronometry reveals headward propagation of erosion in an alpine landscape. Science 332, 84.

Smith, D.E., Stewart, I.S., Harrison, S. and Firth, C.R., 2009. Late Quaternary neotectonics and mass movement in South East Raasay, Inner Hebrides, Scotland. Proceedings of the Geologists' Association, 120(2-3), 145-154.

Sparks, B.W., 1960. Geomorphology. Longmans, London. 371 pp.

Stead, D., Eberhardt, E., Coggan, J.S., 2006. Developments in the characterization of complex rock slope deformation and failure using numerical modelling techniques. Engineering Geology 83, 217-235.

Sternai, P., Herman, F., Valla, P.G., Champagnac, J-D., 2013. Spatial and temporal variations of glacial erosion in the Rhône valley (Swiss Alps): Insights from numerical modelling. Earth and Planetary Science Letters 368, 119–131.

Stewart, I.S., Sauber, S., Rose, J., 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. Quaternary Science Reviews 19, 1367-1389.

Sugden, D.E., 1968. The selectivity of glacial erosion in the Cairngorm Mountains, Scotland. Transactions of the Institute of British Geographers 45, 79-92.

Sugden, D.E., Fogwill, C.J., Hein, A.S., Stuart, F.M., Kerr, A.R., Kubik, P.W., 2014. Emergence of the Shackleton Range from beneath the Antarctic Ice Sheet due to glacial erosion. Geomorphology, 208, 190-199.

Ustaszewski M., Pfiffner O. A., 2008. Neotectonic faulting, uplift and seismicity in the Central and Western Swiss Alps. In: Sigmund S. et al. (Eds.), Tectonic aspects of the Alpine–Carpathian–Dinaride system. Geological Society of London Special Publication 298, 231–249.

Varnes, D. J., 1978. Slope movement types and processes. In: Schuster, R.L., Kruzek, R.J. (Eds.), Landslides, analysis and control. Transportation Research Board, Washington DC, Special Report 176, 11-33.

Watters, R.J., **19**72. Slope stability in the metamorphic rock of the Scottish Highlands. PhD thesis. University of London.

Whalley, W.B., Douglas, G.R., Jonsson, A., 1983. The magnitude and frequency of large rock slides in Iceland during the postglacial. Geografiska Annaler 65A, 99-109.

Wilson, P., 2005. Paraglacial rock-slope failures in Wasdale, western Lake District, England: morphology, styles and significance. Proceedings of the Geologists' Association 116, 349-361.

Wilson, P., Jarman, D., 2015. Rock slope failure in the Lake District; and the Robinson rock slope failure. In: McDougall, D.A., Evans, D.J.A. (Eds.), The Quaternary of the Lake District - Field Guide. Quaternary Research Association, London, pp. 83-95, 201-211.

Wilson, P., Smith, A., 2006. Geomorphological characteristics and significance of Late Quaternary paraglacial rock-slope failures on Skiddaw Group terrain, Lake District, northwest England. Geografiska Annaler 88A, 237-253.

Wilson, P., Clark, R., Smith, A., 2004. Rock-slope failures in the Lake District: a preliminary report. Proceedings of the Cumberland Geological Society 7, 13–36.

Wood, J.L., Harrison, S., Reinhardt, L., 2015. Landslide inventories for climate impacts research in the European Alps. Geomorphology 228, 398–408.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Σ RSFs	def	prob	poss	V	S	R	cata	slide	def'm	RSF area km^2	average size km^2	<0.05 km^2	>0.25 km^2
1 NW Highlands	324	225	59	40	208	91	25	56	154	114	**63.90**	0.20	89	70
2 Grampian Highlands	522	374	83	65	386	118	18	111	209	202	**97.50**	0.19	136	105
Σ Highlands	**846**	**599**	**142**	**105**	**594**	**209**	**43**	**167**	**363**	**316**	**161.40**	**0.19**	**225**	**175**
3 Southern Uplands	37	24	8	5	32	4	1	2	16	19	**5.13**	0.14	9	5
4 Lake District	73	51	15	7	49	18	6	12	26	35	**13.27**	0.18	17	14
5-6 Wales	47	24	12	11	17	14	16	14	17	16	**7.86**	0.17	6	10
Σ British Mountains	**1003**	**698**	**177**	**128**	**692**	**245**	**66**	**195**	**422**	**386**	**186.01**	**0.19**	**257**	**204**
% all RSFs		70%	17%	13%	69%	24%	7%	19%	42%	39%			26%	20%

Table 1 RSF in the British mountains – Summary of the Inventory

NOTES (by column)

1 Mountain areas as Fig. 1 (Wales comprises 5 Snowdonia and 6 Cambrian Mts)
2 Identified from all sources, to Feb 2015
3-5 Status (probability of being a true RSF): def – definite; prob – probable; poss – possible (excludes many other anomalies noted)
6-8 Verification: V – visited in the field; S – seen in the field or on imagery; R – other reports
9-11 RSF character (see Fig 3a) - predominant type where complex
cata – cataclasmic, including sub-cataclasmic: largely disintegrated, travel to slopefoot (4%)/lower slope (15%)
slide – arrested translational slide: distinct cavity and slipmass, retaining some coherence of fabric
def'm – slope deformation: some or all margins diffuse, extensional (27%) if with source scarp or open fractures, compressional (11%) if tight
12 Total land area affected by RSF, including cavities, travel paths, deposits
14-15 Numbers of 'small' and 'large' RSFs

TABLE 3 Regional and local concentration of RSF in the Scottish Highlands

	Area (Km^2)	% of mountain area	RSF area km^2	% of total mountain area	Σ RSFs	% of RSF population
Total Mountain Area	21000		161.4	0.77%	846	100
				% of total RSF area		
Massif cores (25)	5165	25%	156.5	97%	811	96%
Main clusters (8)	3100	15%	122.2	76%	546	65%
Local concentrations (29)	1496	7%	101.4	63%	449	53%
Clusters (Fig 4)						
1 Affric-Kintail-Glenshiel	675		29.1	4%	111	
2 Glenfinnan-Knoydart	265		12.4	4.7%	41	
3 Roy-Lochy	120		7.7	6.5%	21	
4 Lochaber	350		10.8	3.1%	73	
5 Cowal-Arrochar-Luss	450		23.2	5.2%	130	
6 Ericht-Gaick	330		5.9	1.8%	25	
7 Trossachs-Glen Ample	180		9.2	5.1%	33	
8 Glen Almond	110		6.6	5.9%	33	

overall umbrella term	RSF (Rock Slope Failure)		
three main landform types	Rock Slope Deformation (RSD) extensional / compressional	Rockslide	Rock avalanche cataclasmic / sub-cataclasmic
typical landform character	➢ boundaries diffuse (some/all) ➢ short travel ➢ failed mass retains much integrity	➢ boundaries clear (cavity--slipmass) ➢ short--medium travel ➢ failed mass retains some integrity	➢ cavity above debris mass ➢ long--very long travel ➢ failed mass disintegrated

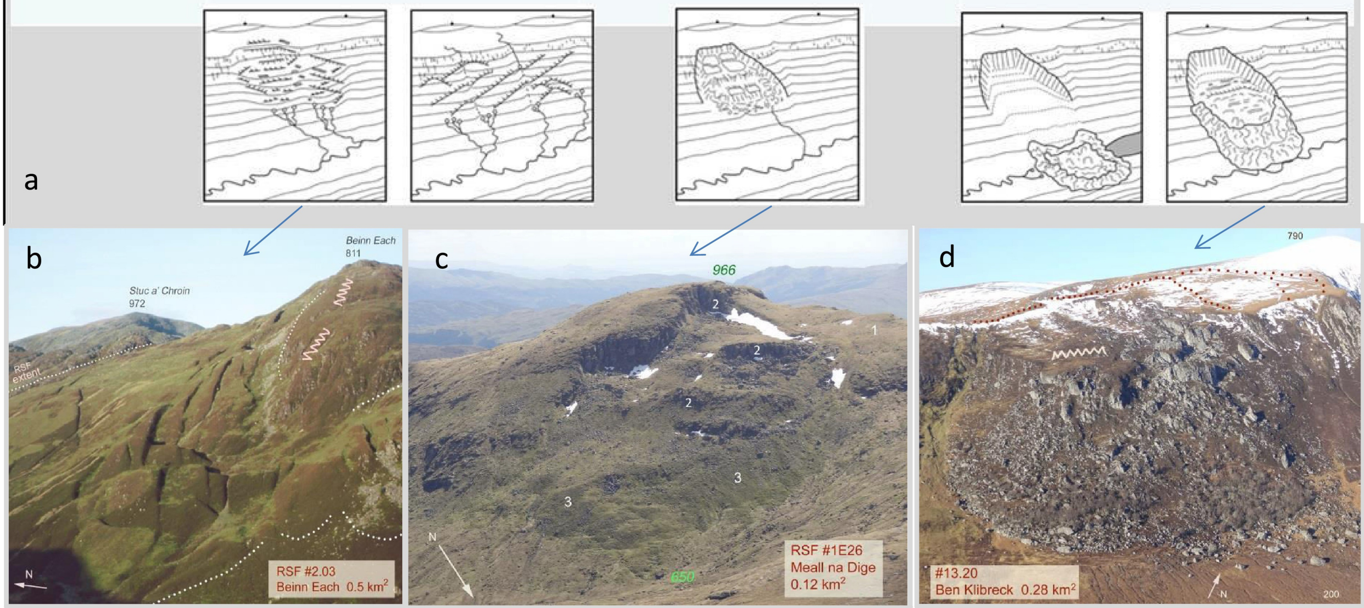


Figure 1

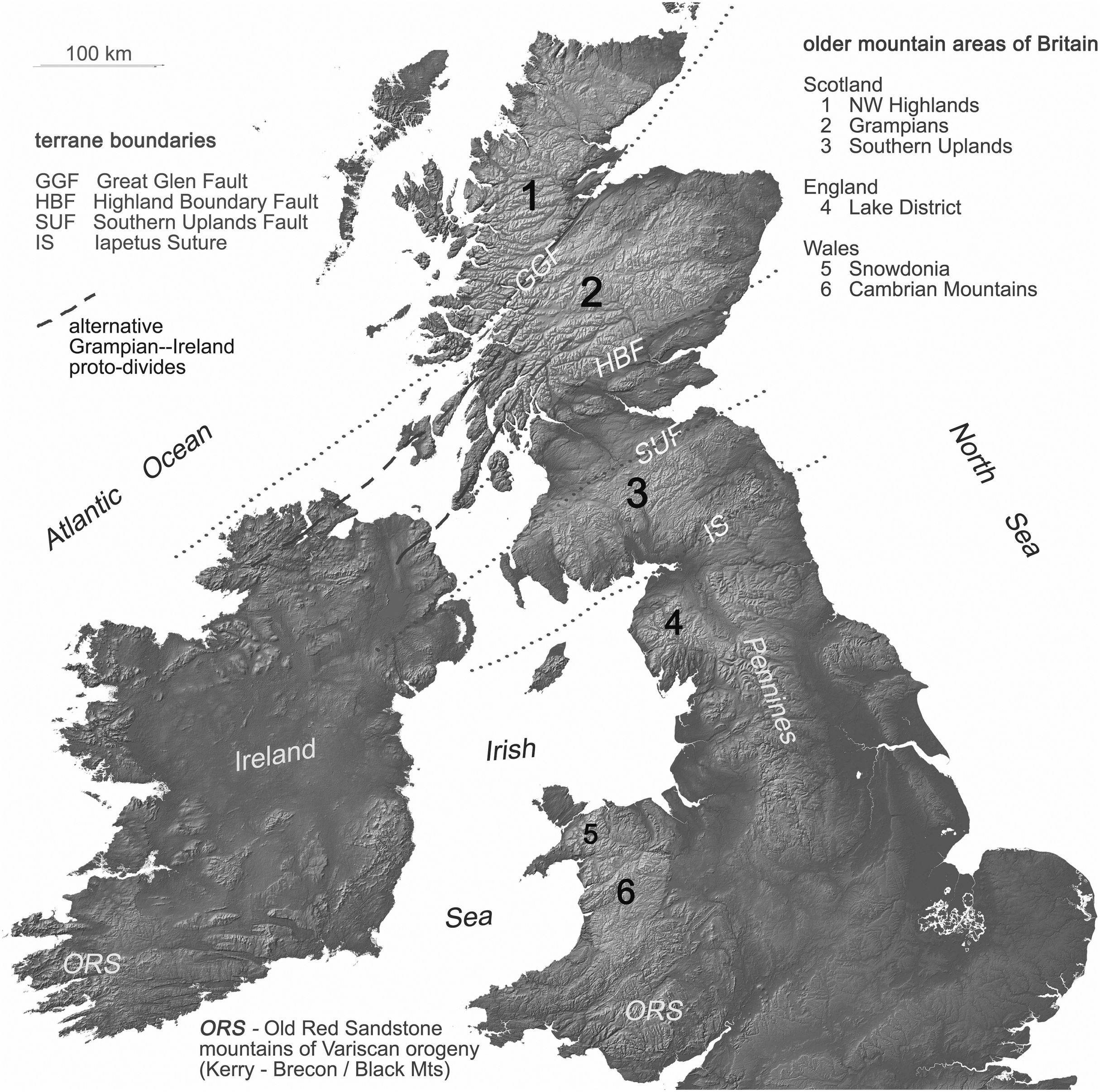

100 km
terrane boundaries
GGF Great Glen Fault
HBF Highland Boundary Fault
SUF Southern Uplands Fault
IS Iapetus Suture
alternative Grampian--Ireland proto-divides
older mountain areas of Britain
Scotland
1 NW Highlands
2 Grampians
3 Southern Uplands
England
4 Lake District
Wales
5 Snowdonia
6 Cambrian Mountains
Atlantic Ocean
North Sea
Irish Sea
Ireland
Pennines
GGF
HBF
SUF
IS
1
2
3
4
5
6
ORS
ORS
ORS - Old Red Sandstone mountains of Variscan orogeny (Kerry - Brecon / Black Mts)

Figure 2

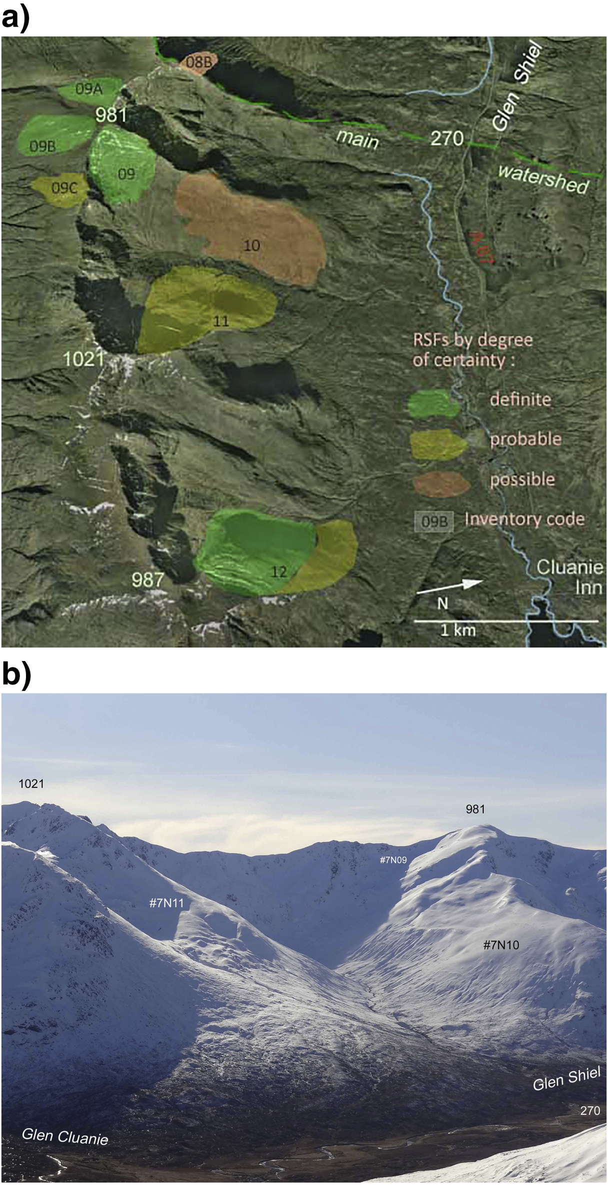

a)
08B
09A
981
09B
09
09C
10
11
1021
12
987
main
270
watershed
Glen Shiel
RSFs by degree
of certainty :
definite
probable
possible
09B
Inventory code
Cluanie
Inn
N
1 km
b)
1021
981
#7N09
#7N11
#7N10
Glen Shiel
270
Glen Cluanie

Figure 3

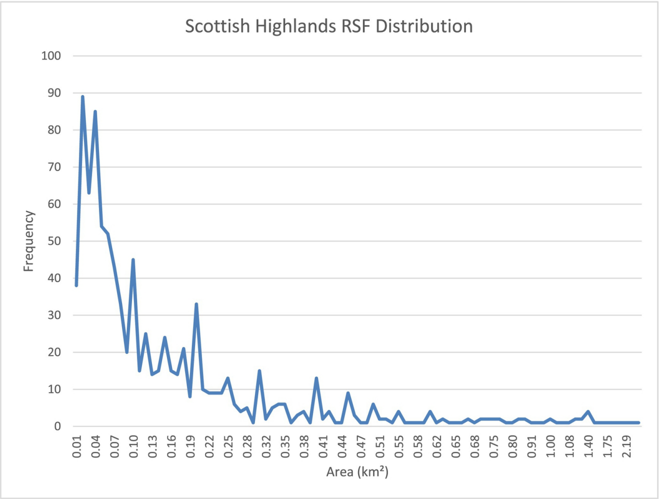
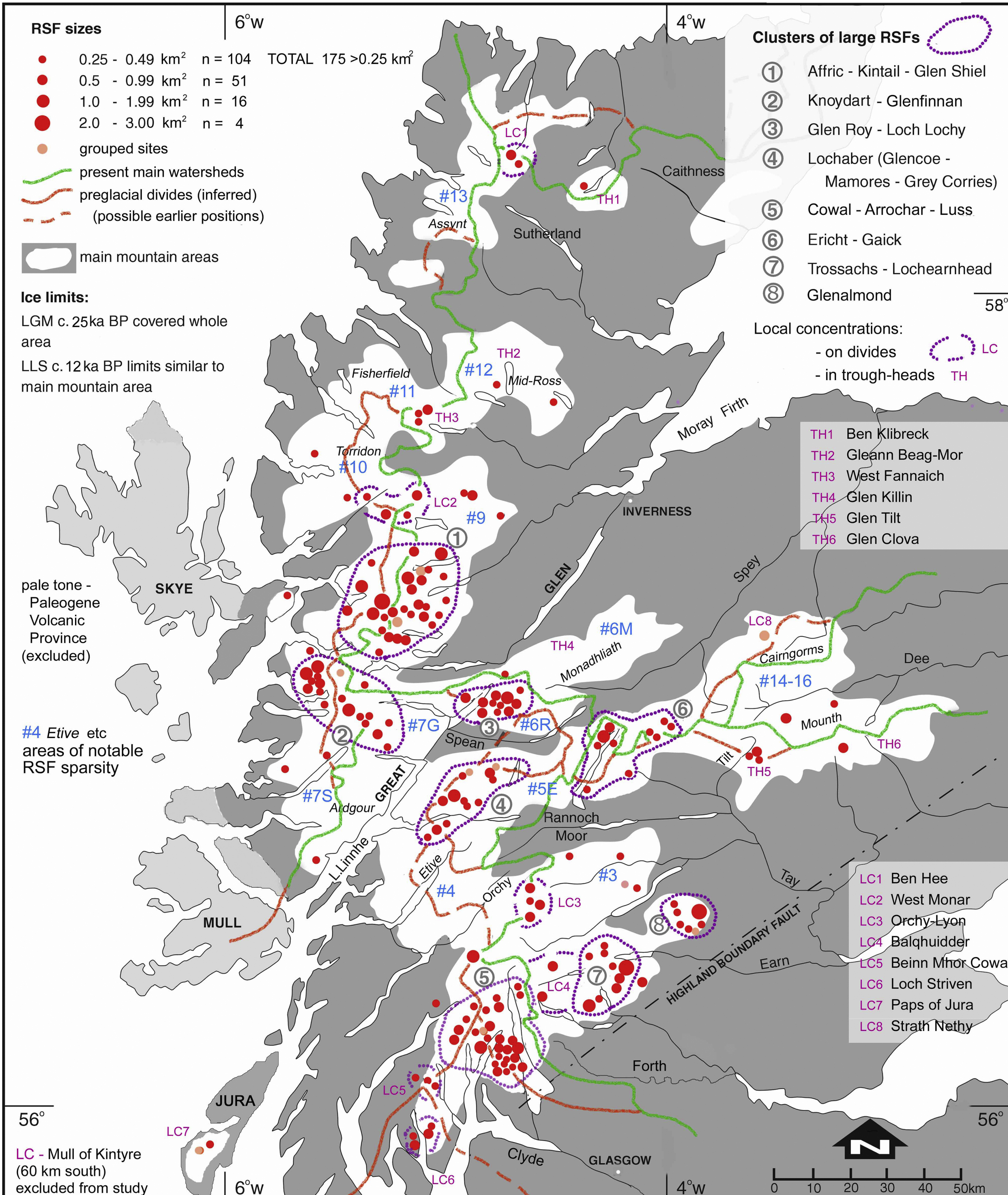

Scottish Highlands RSF Distribution
Frequency
100
90
80
70
60
50
40
30
20
10
0
0.01
0.04
0.07
0.10
0.13
0.16
0.19
0.22
0.25
0.28
0.32
0.35
0.38
0.41
0.44
0.47
0.51
0.55
0.58
0.62
0.65
0.68
0.75
0.80
0.91
1.00
1.08
1.40
1.75
2.19
Area (km²)

Figure 4



RSF sizes
0.25 - 0.49 km² n = 104 TOTAL 175 >0.25 km²
0.5 - 0.99 km² n = 51
1.0 - 1.99 km² n = 16
2.0 - 3.00 km² n = 4
grouped sites
present main watersheds
preglacial divides (inferred)
(possible earlier positions)
main mountain areas
Ice limits:
LGM c. 25ka BP covered whole area
LLS c. 12ka BP limits similar to main mountain area
pale tone - Paleogene Volcanic Province (excluded)
#4 Etive etc areas of notable RSF sparsity
LC - Mull of Kintyre (60 km south) excluded from study
Clusters of large RSFs
1 Affric - Kintail - Glen Shiel
2 Knoydart - Glenfinnan
3 Glen Roy - Loch Lochy
4 Lochaber (Glencoe - Mamores - Grey Corries)
5 Cowal - Arrochar - Luss
6 Ericht - Gaick
7 Trossachs - Lochearnhead
8 Glenalmond
Local concentrations:
- on divides LC
- in trough-heads TH
TH1 Ben Klibreck
TH2 Gleann Beag-Mor
TH3 West Fannaich
TH4 Glen Killin
TH5 Glen Tilt
TH6 Glen Clova
LC1 Ben Hee
LC2 West Monar
LC3 Orchy-Lyon
LC4 Balquhidder
LC5 Beinn Mhor Cowal
LC6 Loch Striven
LC7 Paps of Jura
LC8 Strath Nethy
6°w
4°w
58°
56°
Caithness
Sutherland
Assynt
Fisherfield
Mid-Ross
Torridon
Moray Firth
INVERNESS
GLEN
GREAT
SKYE
Monadhliath
Spey
Cairngorms
Dee
Mounth
Tilt
Spean
Ardgour
L.Linnhe
Etive
Orchy
Rannoch Moor
Tay
HIGHLAND BOUNDARY FAULT
Earn
Forth
Clyde
GLASGOW
MULL
JURA
#13 #12 #11 #10 #9 #6M #14-16 #7G #6R #5E #7S #4 #3
0 10 20 30 40 50km

Figure 5

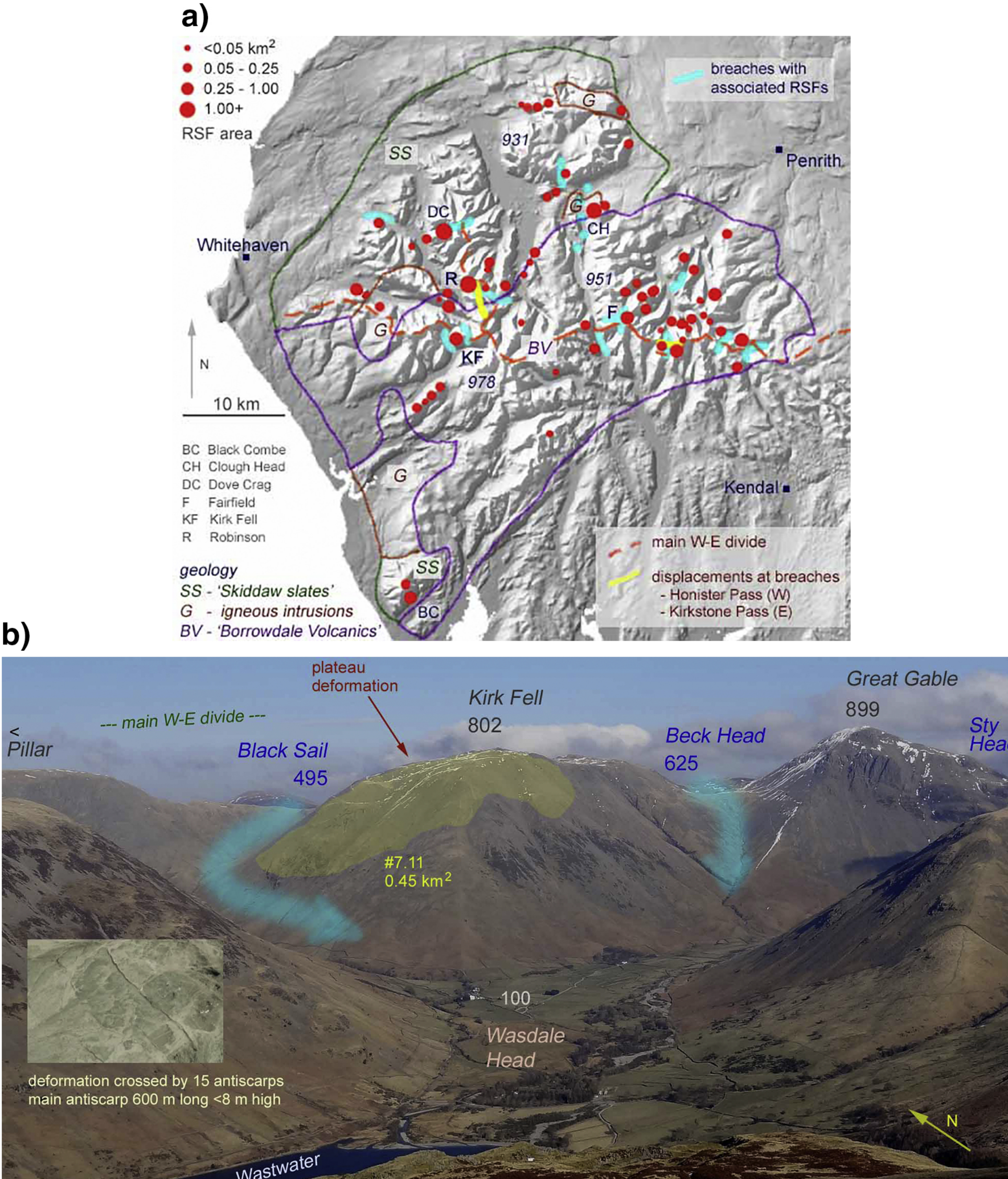

a)
<0.05 km2
0.05 - 0.25
0.25 - 1.00
1.00+
RSF area
breaches with associated RSFs
Penrith
Whitehaven
Kendal
SS
G
931
DC
CH
R
951
F
KF
978
BV
N
10 km
BC Black Combe
CH Clough Head
DC Dove Crag
F Fairfield
KF Kirk Fell
R Robinson
geology
SS - 'Skiddaw slates'
G - igneous intrusions
BV - 'Borrowdale Volcanics'
main W-E divide
displacements at breaches
- Honister Pass (W)
- Kirkstone Pass (E)
BC
b)
plateau deformation
Kirk Fell
802
Great Gable
899
--- main W-E divide ---
< Pillar
Black Sail
495
Beck Head
625
Sty Head
#7.11
0.45 km2
100
Wasdale Head
deformation crossed by 15 antiscarps
main antiscarp 600 m long <8 m high
Wastwater
N

Figure 6

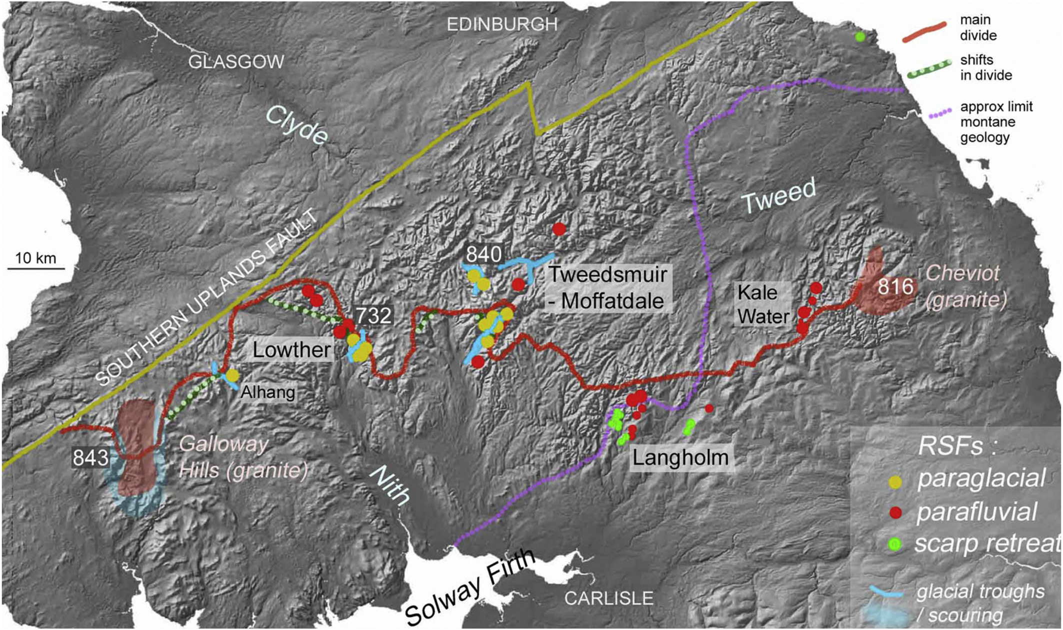
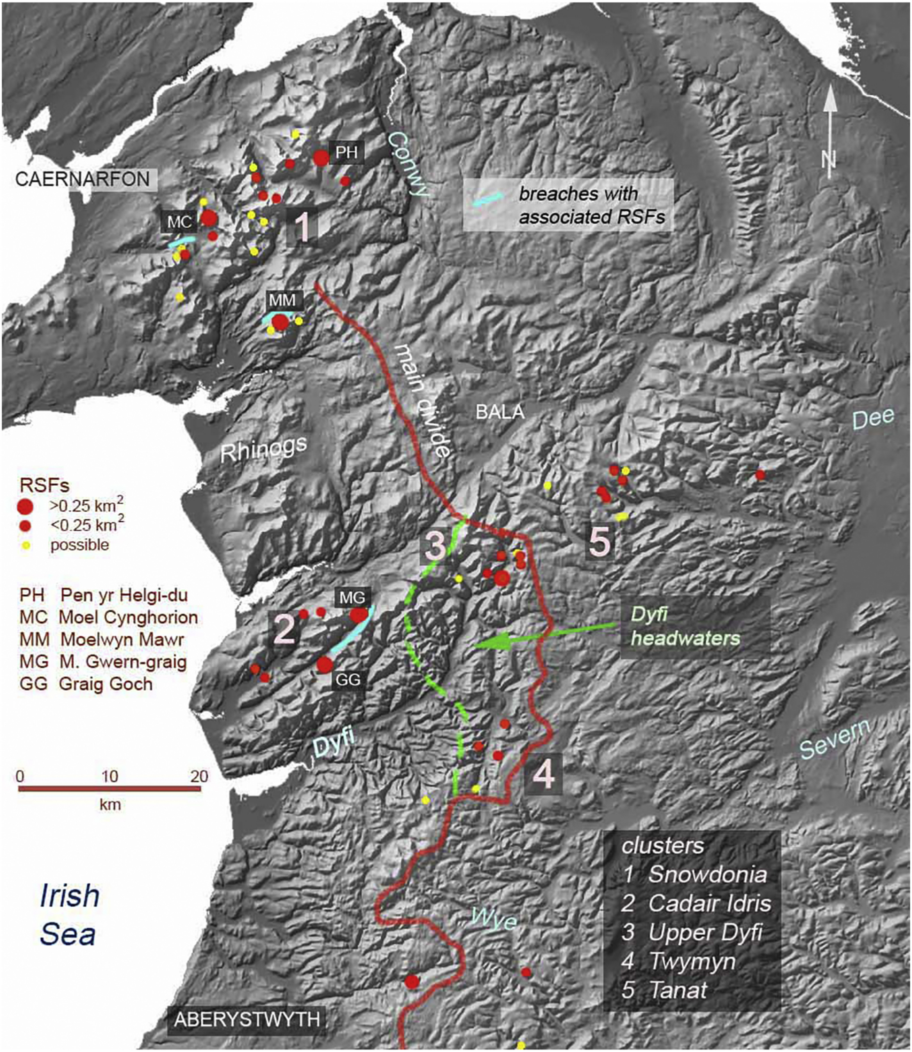

EDINBURGH
GLASGOW
Clyde
main divide
shifts in divide
approx limit montane geology
Tweed
SOUTHERN UPLANDS FAULT
10 km
840
Tweedsmuir - Moffatdale
Kale Water
816
Cheviot (granite)
732
Lowther
Alhang
843
Galloway Hills (granite)
Nith
Langholm
RSFs :
paraglacial
parafluvial
scarp retreat
glacial troughs / scouring
Solway Firth
CARLISLE

Figure 7



CAERNARFON
PH
MC
MM
1
Conwy
breaches with
associated RSFs
N
main divide
BALA
Rhinogs
Dee
RSFs
>0.25 km^2
<0.25 km^2
possible
3
5
PH Pen yr Helgi-du
MC Moel Cynghorion
MM Moelwyn Mawr
MG M. Gwern-graig
GG Graig Goch
MG
2
GG
Dyfi
headwaters
Dyfi
Severn
0 10 20
km
4
Irish
Sea
clusters
1 Snowdonia
2 Cadair Idris
3 Upper Dyfi
4 Twymyn
5 Tanat
Wye
ABERYSTWYTH

Figure 8

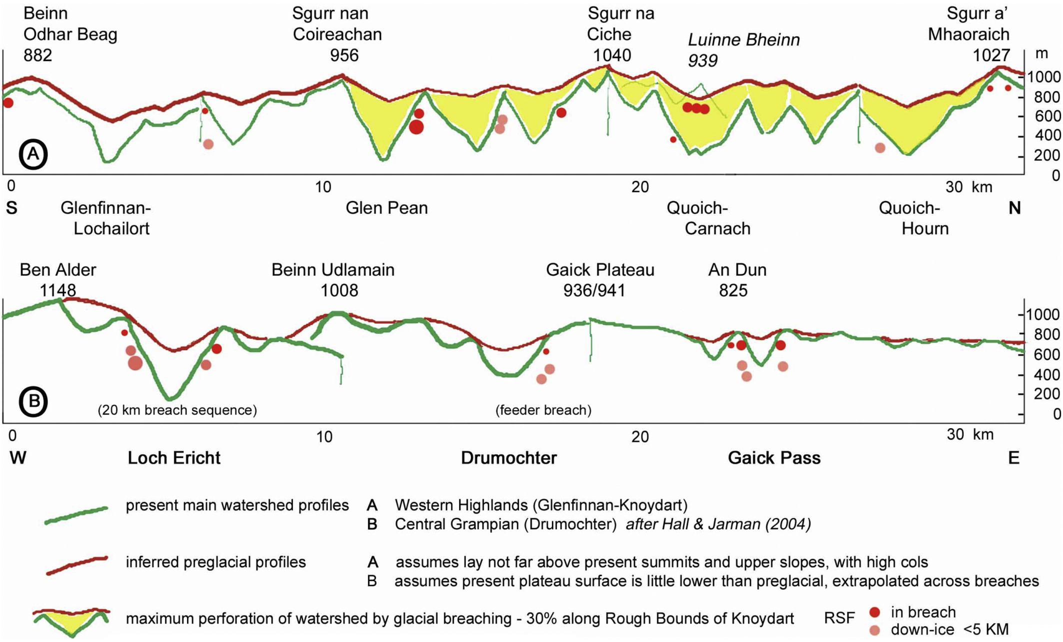

Beinn Odhar Beag 882
Sgurr nan Coireachan 956
Sgurr na Ciche 1040
Luinne Bheinn 939
Sgurr a' Mhaoraich 1027
m
1000
800
600
400
200
0
A
0
10
20
30 km
S
Glenfinnan-Lochailort
Glen Pean
Quoich-Carnach
Quoich-Hourn
N
Ben Alder 1148
Beinn Udlamain 1008
Gaick Plateau 936/941
An Dun 825
B
(20 km breach sequence)
(feeder breach)
W
Loch Ericht
Drumochter
Gaick Pass
E
present main watershed profiles
A Western Highlands (Glenfinnan-Knoydart)
B Central Grampian (Drumochter) after Hall & Jarman (2004)
inferred preglacial profiles
A assumes lay not far above present summits and upper slopes, with high cols
B assumes present plateau surface is little lower than preglacial, extrapolated across breaches
maximum perforation of watershed by glacial breaching - 30% along Rough Bounds of Knoydart
RSF
in breach
down-ice <5 KM

Figure 9

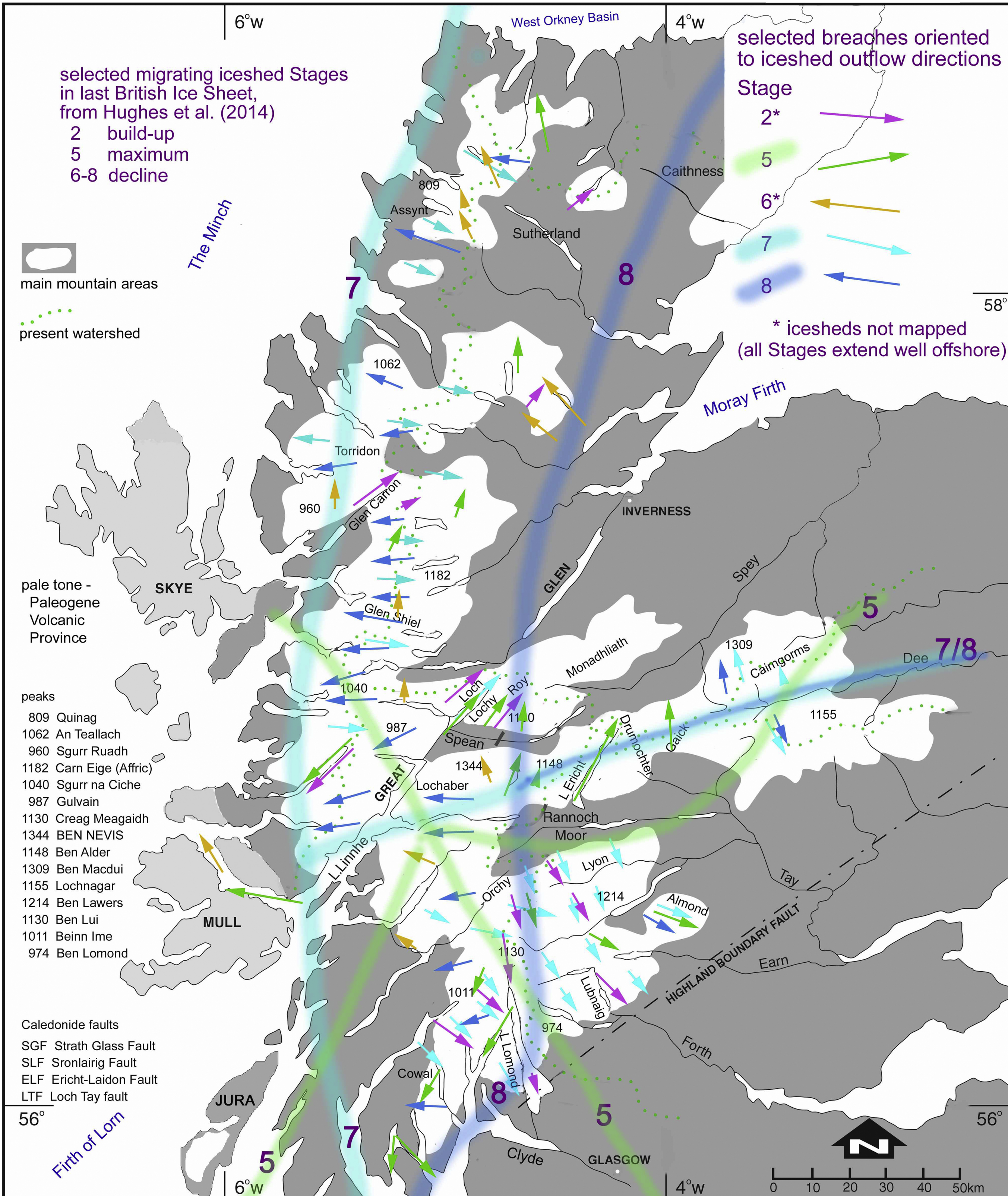
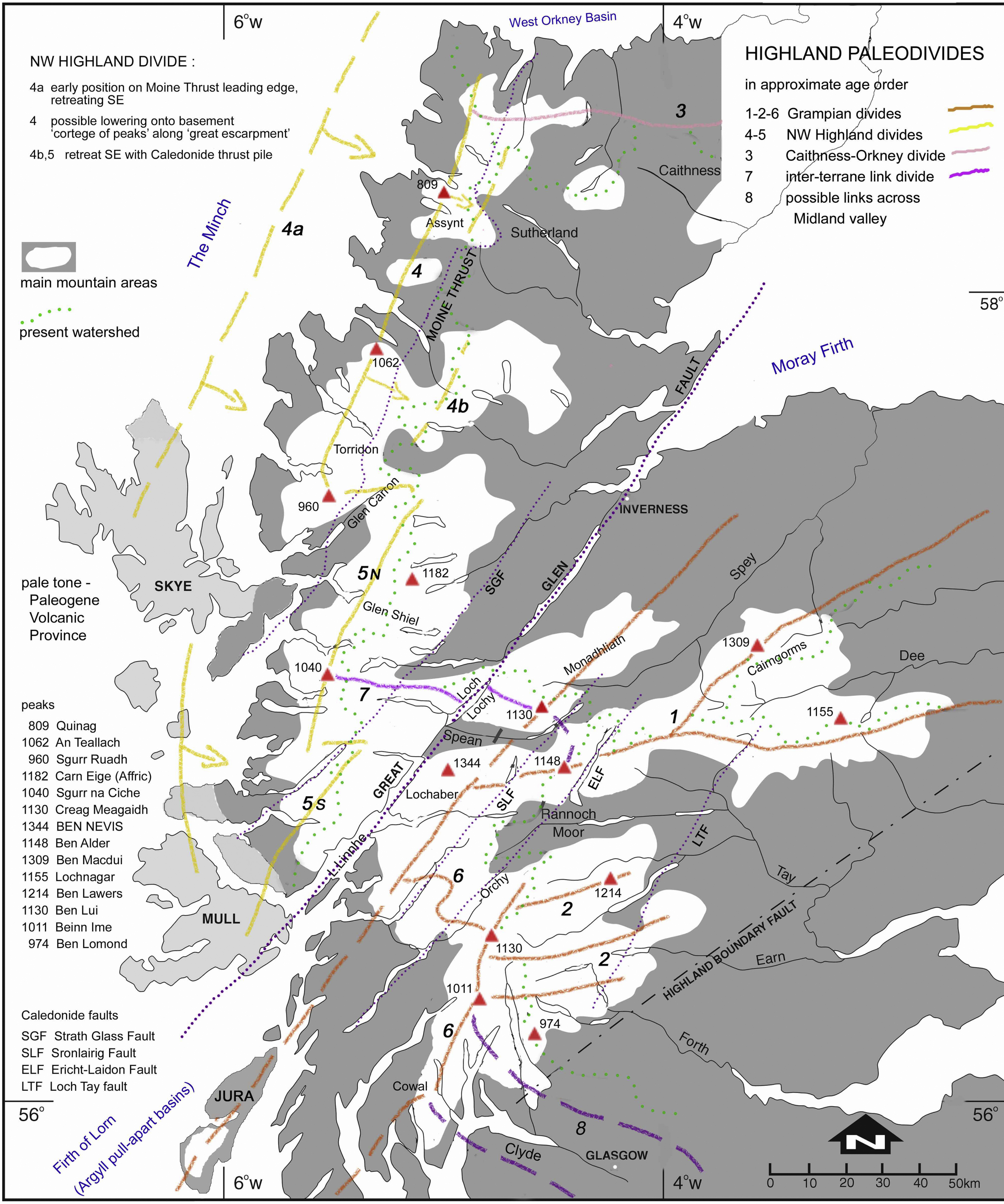
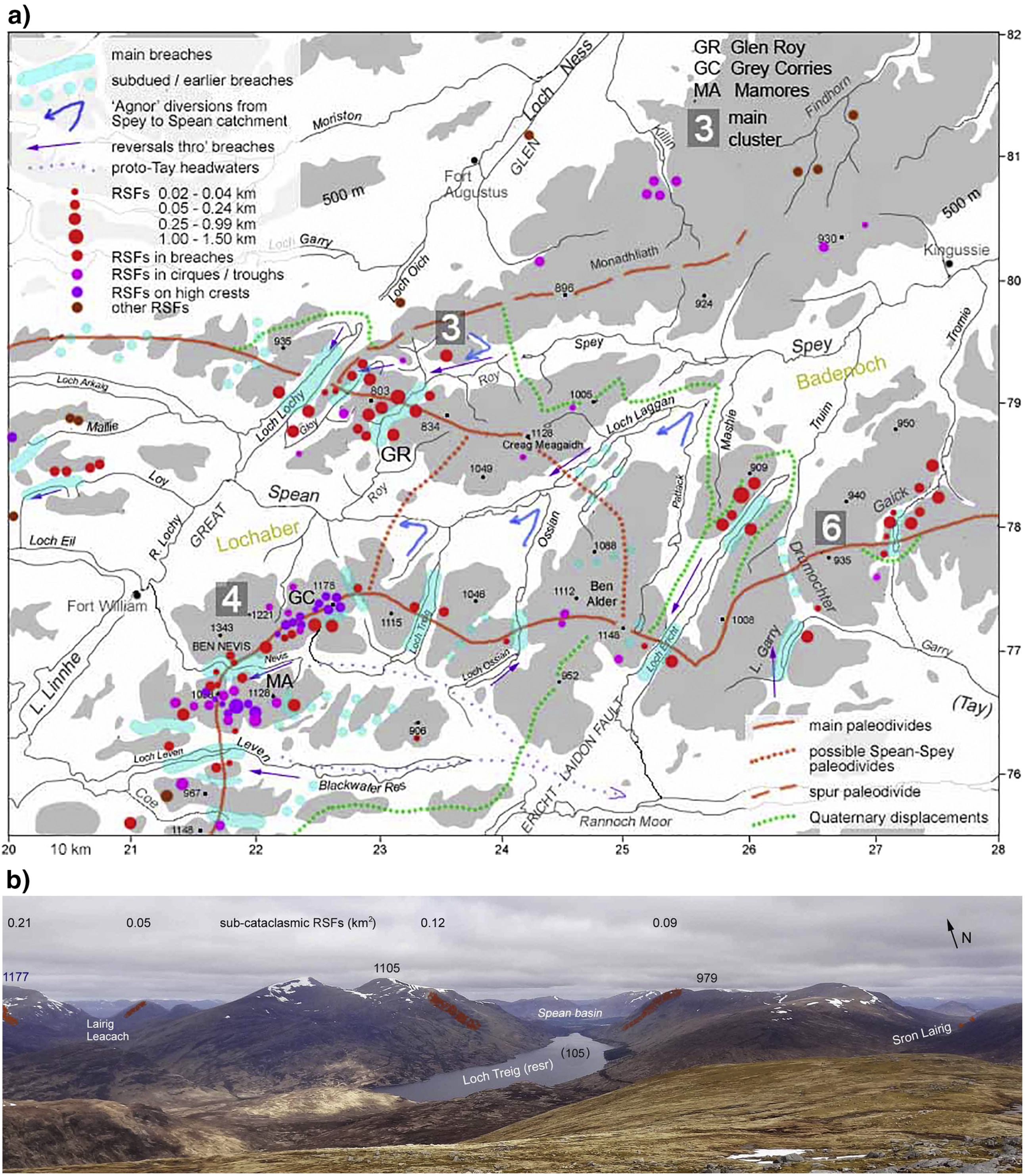

selected migrating iceshed Stages
in last British Ice Sheet,
from Hughes et al. (2014)
2 build-up
5 maximum
6-8 decline
selected breaches oriented
to iceshed outflow directions
Stage
2*
5
6*
7
8
* iceshed not mapped
(all Stages extend well offshore)
main mountain areas
present watershed
pale tone -
Paleogene
Volcanic
Province
peaks
809 Quinag
1062 An Teallach
960 Sgurr Ruadh
1182 Carn Eige (Affric)
1040 Sgurr na Ciche
987 Gulvain
1130 Creag Meagaidh
1344 BEN NEVIS
1148 Ben Alder
1309 Ben Macdui
1155 Lochnagar
1214 Ben Lawers
1130 Ben Lui
1011 Beinn Ime
974 Ben Lomond
Caledonide faults
SGF Strath Glass Fault
SLF Sronlairig Fault
ELF Ericht-Laidon Fault
LTF Loch Tay fault
West Orkney Basin
The Minch
Moray Firth
Firth of Lorn
Caithness
Sutherland
Assynt
Torridon
Glen Carron
Glen Shiel
SKYE
MULL
JURA
INVERNESS
GLASGOW
GREAT GLEN
Monadhliath
Cairngorms
Spey
Dee
Drumochter
Gaick
L Ericht
Loch Lochy
Roy
Spean
Lochaber
Rannoch Moor
L.Linnhe
Orchy
Lyon
Almond
Tay
Earn
Forth
Lubnaig
L Lomond
Cowal
Clyde
HIGHLAND BOUNDARY FAULT
6°w
4°w
58°
56°
0 10 20 30 40 50km

Figure 10



HIGHLAND PALEODIVIDES
in approximate age order
1-2-6 Grampian divides
4-5 NW Highland divides
3 Caithness-Orkney divide
7 inter-terrane link divide
8 possible links across Midland valley
NW HIGHLAND DIVIDE :
4a early position on Moine Thrust leading edge, retreating SE
4 possible lowering onto basement 'cortege of peaks' along 'great escarpment'
4b,5 retreat SE with Caledonide thrust pile
main mountain areas
present watershed
pale tone - Paleogene Volcanic Province
peaks
809 Quinag
1062 An Teallach
960 Sgurr Ruadh
1182 Carn Eige (Affric)
1040 Sgurr na Ciche
1130 Creag Meagaidh
1344 BEN NEVIS
1148 Ben Alder
1309 Ben Macdui
1155 Lochnagar
1214 Ben Lawers
1130 Ben Lui
1011 Beinn Ime
974 Ben Lomond
Caledonide faults
SGF Strath Glass Fault
SLF Sronlairig Fault
ELF Ericht-Laidon Fault
LTF Loch Tay fault
6°w
4°w
58°
56°
West Orkney Basin
The Minch
Moray Firth
Firth of Lorn
(Argyll pull-apart basins)
Caithness
Sutherland
Assynt
MOINE THRUST
Torridon
Glen Carron
Glen Shiel
SKYE
MULL
JURA
INVERNESS
GLASGOW
GREAT GLEN FAULT
Loch Lochy
Spean
Lochaber
L.Linnhe
Rannoch Moor
Monadhliath
Cairngorms
Spey
Dee
Tay
Earn
Forth
Clyde
Cowal
Orchy
HIGHLAND BOUNDARY FAULT
0 10 20 30 40 50km

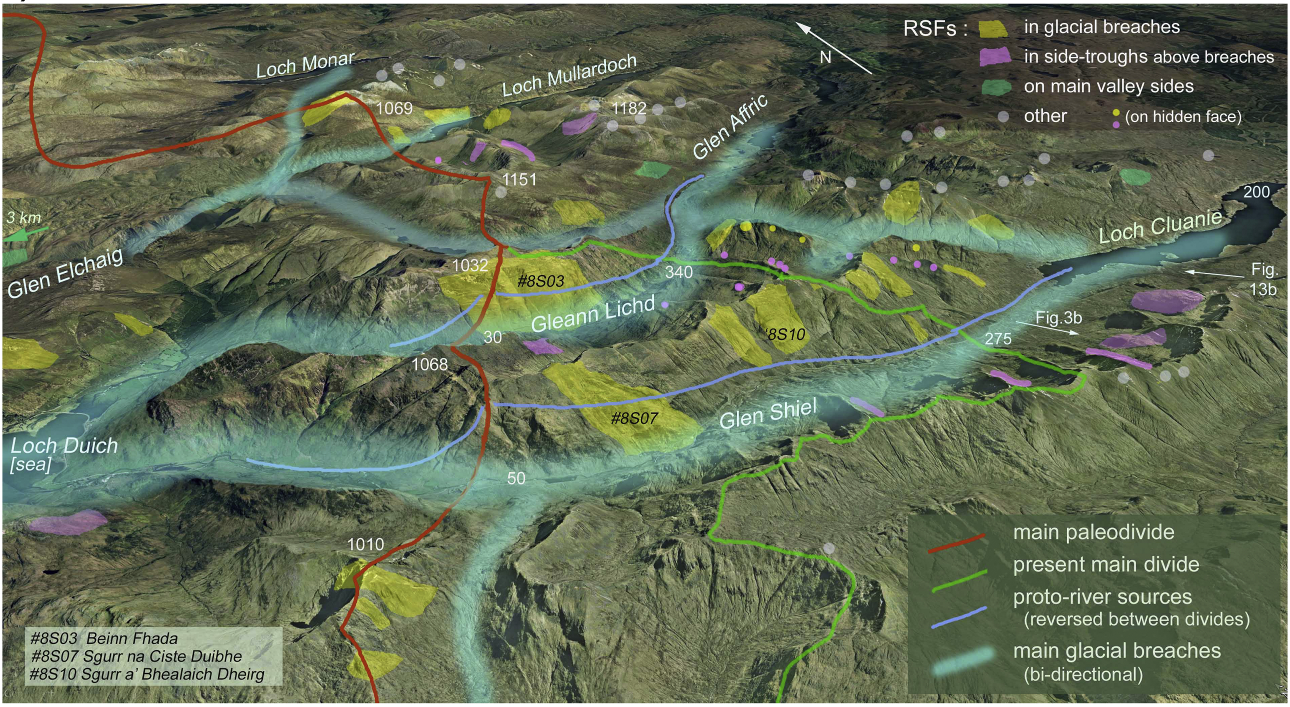
Figure 11



a)
main breaches
subdued / earlier breaches
'Agnor' diversions from Spey to Spean catchment
reversals thro' breaches
proto-Tay headwaters
RSFs 0.02 - 0.04 km
0.05 - 0.24 km
0.25 - 0.99 km
1.00 - 1.50 km
RSFs in breaches
RSFs in cirques / troughs
RSFs on high crests
other RSFs
GR Glen Roy
GC Grey Corries
MA Mamores
3 main cluster
main paleodivides
possible Spean-Spey paleodivides
spur paleodivide
Quaternary displacements
Loch Ness
Moriston
GLEN
Fort Augustus
500 m
Loch Garry
Loch Oich
Monadhliath
Killin
Findhorn
Kingussie
Spey
Badenoch
Tromie
Loch Arkaig
Loch Lochy
Gloy
Roy
Loch Laggan
Creag Meagaidh
Mashie
Truim
Mallie
Loy
Spean
GR
Patlack
Gaick
Loch Eil
R. Lochy
GREAT
Lochaber
Ossian
Drumochter
Fort William
Ben Alder
BEN NEVIS
Nevis
MA
Loch Treig
Loch Ossian
Loch Ericht
L. Garry
Garry
(Tay)
L. Linnhe
Loch Leven
Leven
Blackwater Res
Coe
ERICHT - LAIDON FAULT
Rannoch Moor
10 km
b)
sub-cataclasmic RSFs (km²)
0.21
0.05
0.12
0.09
N
1177
1105
979
Lairig Leacach
Spean basin
Loch Treig (resr)
(105)
Sron Lairig

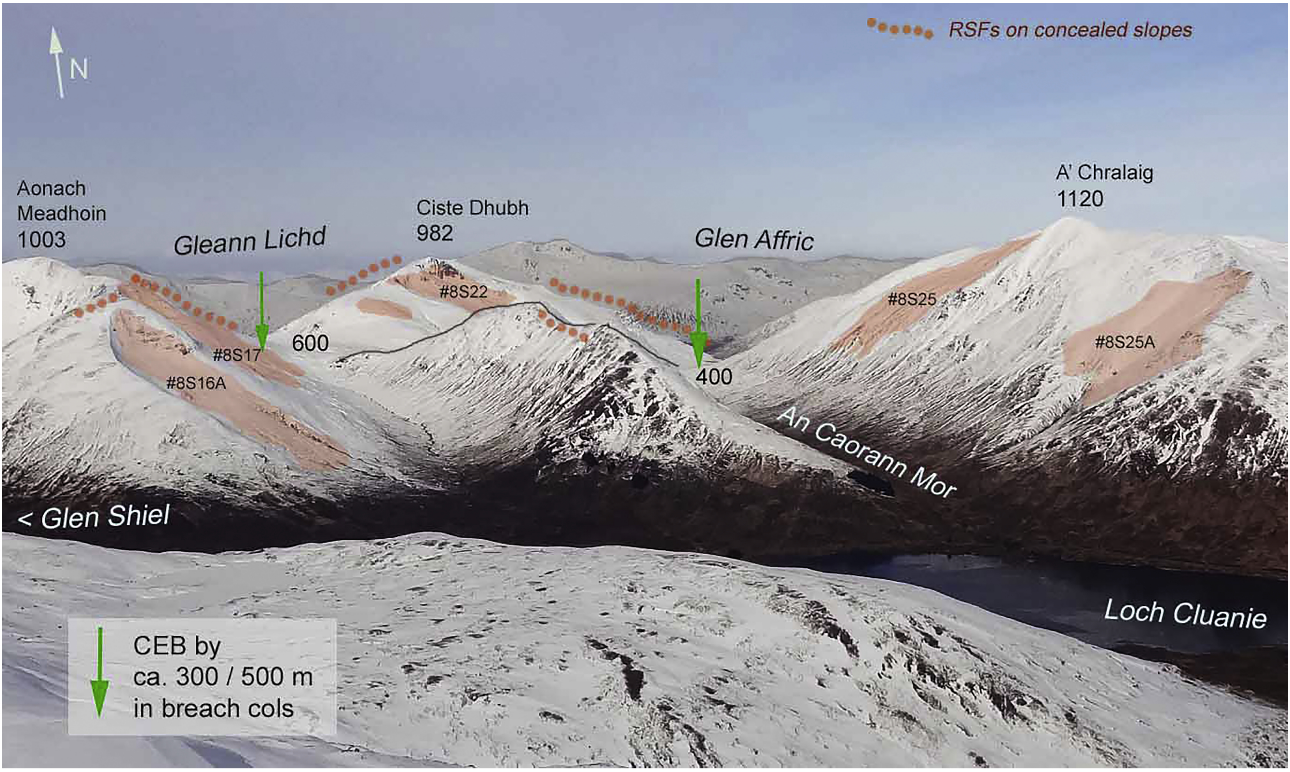
Figure 12

a)



RSFs :
in glacial breaches
in side-troughs above breaches
on main valley sides
other
(on hidden face)
N
Loch Monar
Loch Mullardoch
Glen Affric
Loch Cluanie
Glen Elchaig
Gleann Lichd
Glen Shiel
Loch Duich
[sea]
3 km
1069
1182
1151
1032
340
30
1068
50
1010
275
200
#8S03
'8S10
#8S07
Fig. 13b
Fig.3b
#8S03 Beinn Fhada
#8S07 Sgurr na Ciste Duibhe
#8S10 Sgurr a' Bhealaich Dheirg
main paleodivide
present main divide
proto-river sources
(reversed between divides)
main glacial breaches
(bi-directional)

b)



RSFs on concealed slopes
N
Aonach
Meadhoin
1003
Gleann Lichd
Ciste Dhubh
982
Glen Affric
A' Chralaig
1120
#8S22
#8S25
#8S25A
#8S17
600
#8S16A
400
An Caorann Mor
< Glen Shiel
Loch Cluanie
CEB by
ca. 300 / 500 m
in breach cols

Figure 13

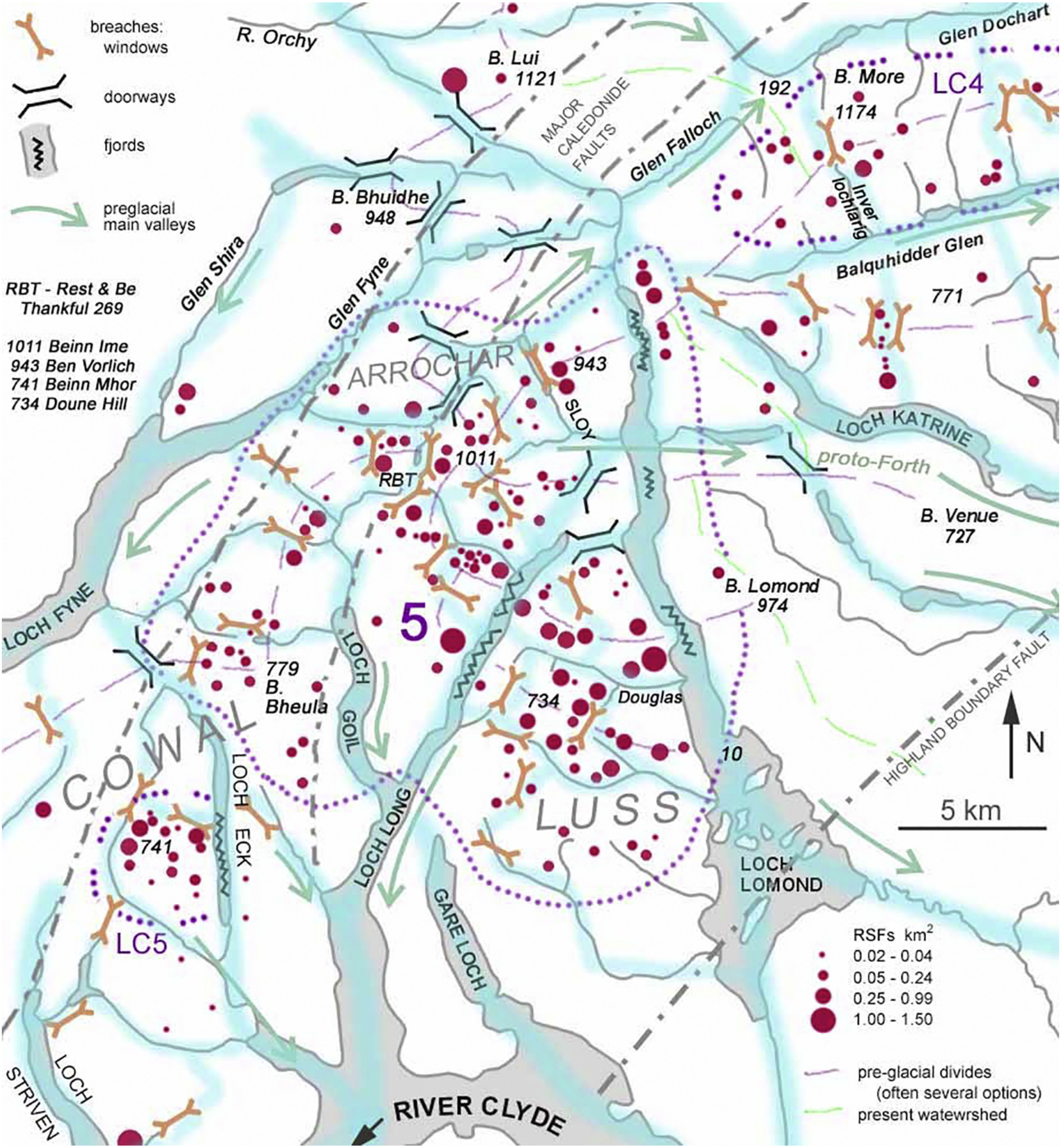
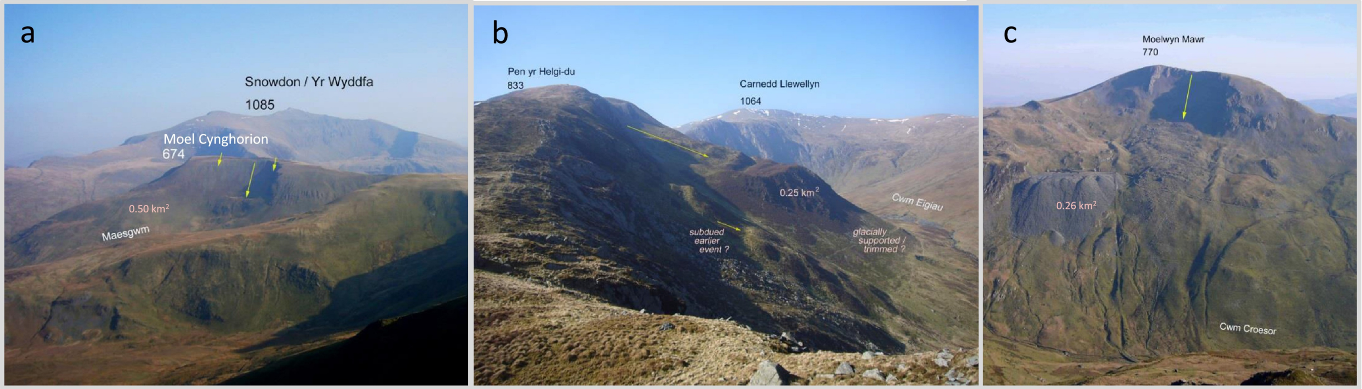

breaches: windows
doorways
fjords
preglacial main valleys
RBT - Rest & Be Thankful 269
1011 Beinn Ime
943 Ben Vorlich
741 Beinn Mhor
734 Doune Hill
R. Orchy
B. Lui 1121
MAJOR CALEDONIDE FAULTS
Glen Falloch
192
B. More 1174
Glen Dochart
LC4
Inver lochlarig
Balquhidder Glen
771
B. Bhuidhe 948
Glen Shira
Glen Fyne
ARROCHAR
943
SLOY
1011
RBT
LOCH KATRINE
proto-Forth
B. Venue 727
B. Lomond 974
LOCH FYNE
5
LOCH GOIL
779 B. Bheula
734
Douglas
COWAL
LOCH ECK
10
HIGHLAND BOUNDARY FAULT
N
5 km
LUSS
LOCH LONG
741
LOCH LOMOND
GARE LOCH
LC5
RSFs km2
0.02 - 0.04
0.05 - 0.24
0.25 - 0.99
1.00 - 1.50
LOCH STRIVEN
RIVER CLYDE
pre-glacial divides (often several options)
present watewrshed

Figure 14



a
Snowdon / Yr Wyddfa
1085
Moel Cynghorion
674
0.50 km²
Maesgwm
b
Pen yr Helgi-du
833
Carnedd Llewellyn
1064
0.25 km²
Cwm Eigiau
subdued earlier event ?
glacially supported / trimmed ?
c
Moelwyn Mawr
770
0.26 km²
Cwm Croesor

Figure 15

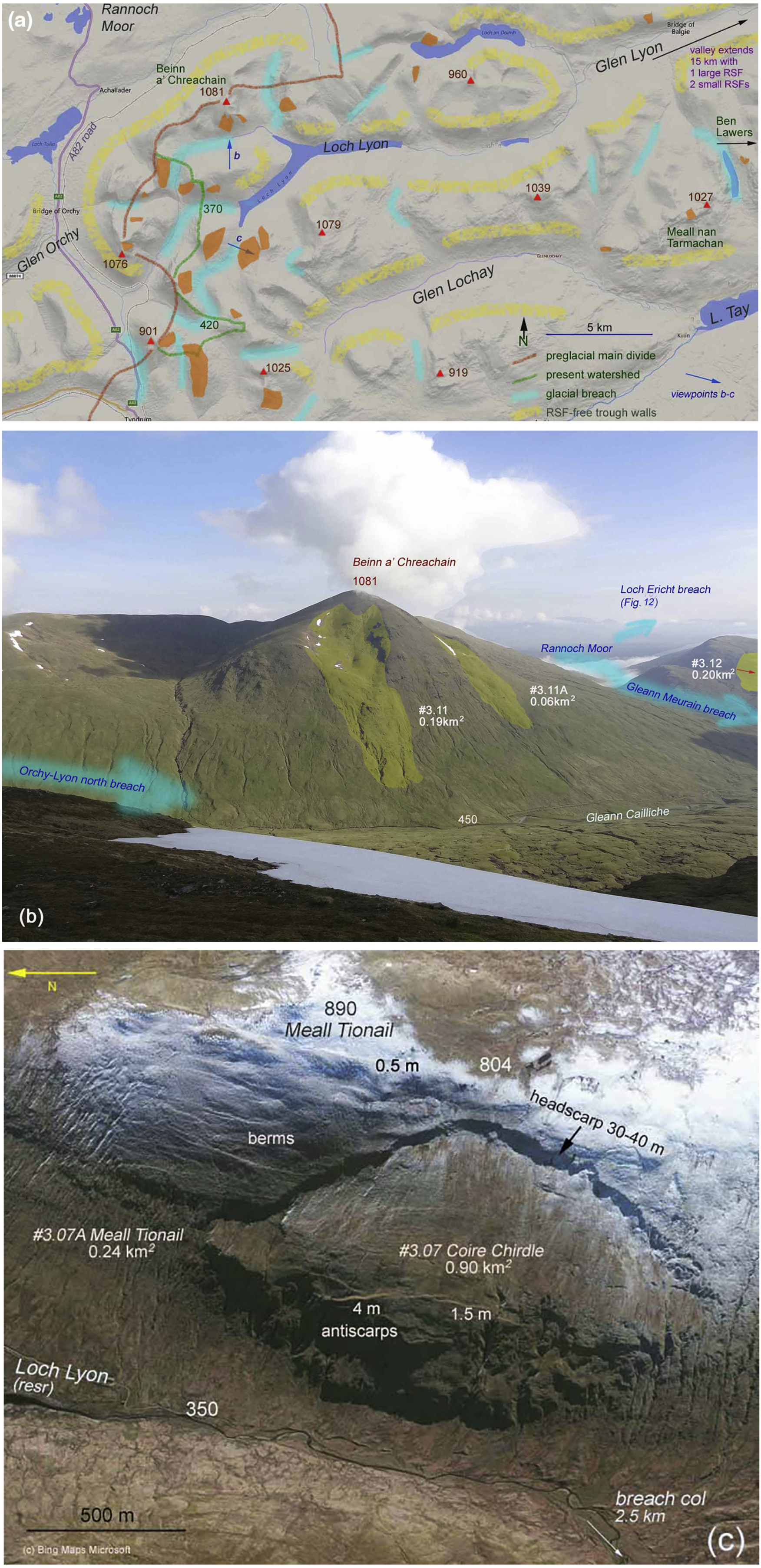
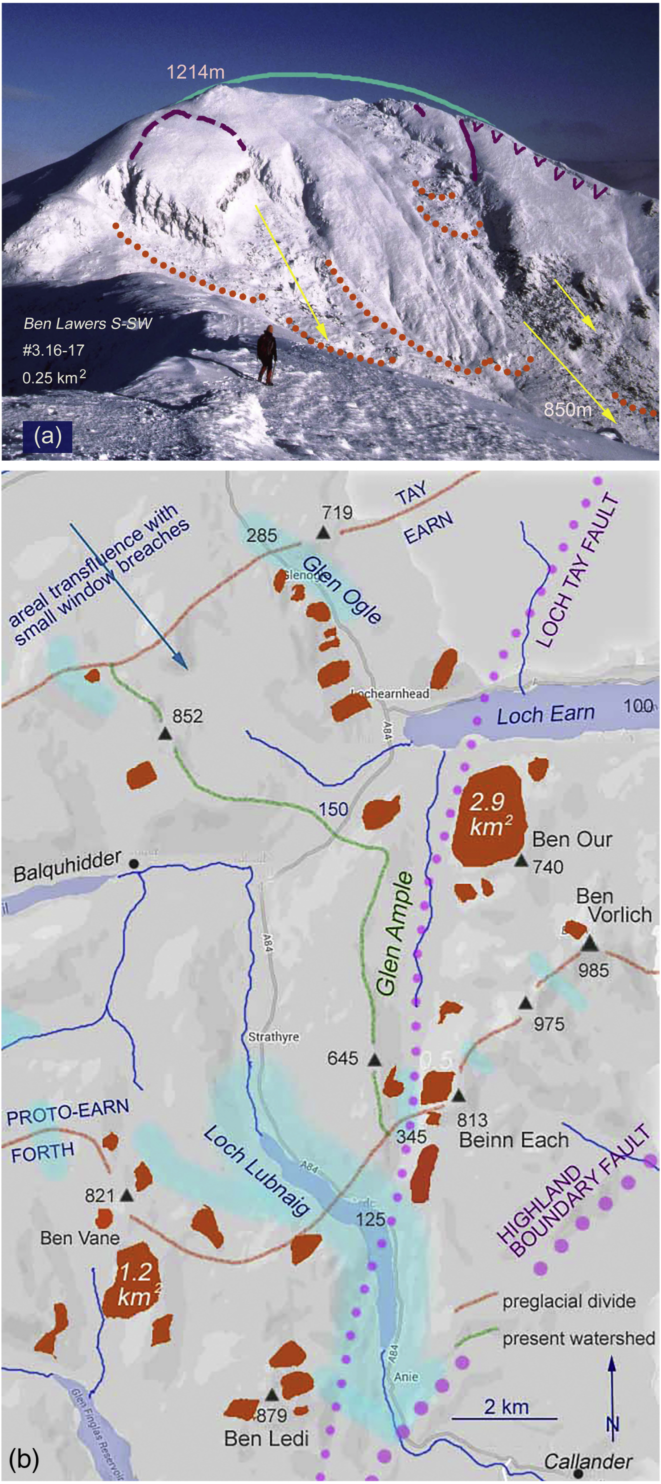

(a)
Rannoch Moor
Beinn a' Chreachain
1081
Achallader
A82 road
Loch Lyon
960
Glen Lyon
Bridge of Balgie
valley extends 15 km with 1 large RSF 2 small RSFs
Ben Lawers
b
370
Bridge of Orchy
1079
1039
1027
Meall nan Tarmachan
c
Glen Orchy
1076
Glen Lochay
420
901
L. Tay
5 km
N
preglacial main divide
present watershed
glacial breach
RSF-free trough walls
viewpoints b-c
1025
919
Tyndrum
Beinn a' Chreachain
1081
Loch Ericht breach (Fig. 12)
Rannoch Moor
#3.12 0.20km²
#3.11A 0.06km²
Gleann Meurain breach
#3.11 0.19km²
Orchy-Lyon north breach
450
Gleann Cailliche
(b)
N
890
Meall Tionail
0.5 m
804
headscarp 30-40 m
berms
#3.07A Meall Tionail 0.24 km²
#3.07 Coire Chirdle 0.90 km²
4 m
1.5 m
antiscarps
Loch Lyon (resr)
350
breach col 2.5 km
500 m
(c) Bing Maps Microsoft
(c)

Figure 16



1214m
Ben Lawers S-SW
#3.16-17
0.25 km^2
850m
(a)
TAY
EARN
719
285
LOCH TAY FAULT
areal transfluence with small window breaches
Glen Ogle
Glenogle
Lochearnhead
Loch Earn
100
852
A84
150
2.9 km^2
Ben Our
740
Balquhidder
Glen Ample
Ben Vorlich
985
975
A84
Strathyre
645
813
Beinn Each
345
PROTO-EARN
FORTH
Loch Lubnaig
A84
HIGHLAND BOUNDARY FAULT
821
125
Ben Vane
1.2 km^2
preglacial divide
present watershed
A84
Anie
2 km
N
879
Ben Ledi
Callander
Glen Finglas Reservoir
(b)

Figure 17